No.229-1

basics of missile guidance and space techniques

by MARVIN HOBBS

VOL. 1

GUIDANCE TECHNIQUES

CONTROL AND GUIDANCE

RADIO & RADAR COMMAND

GUIDE BEAM, DOPPLER
& HOMING TECHNIQUES

GYROSCOPIC FUNDAMENTALS

INERTIAL & CELESTIAL
NAVIGATION

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ACTUATORS

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No.229-2

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VOL. 2

TESTING & TELEMETERING

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MARVIN HOBBS

Basics of Missile Guidance and Space Techniques, Vol. 1

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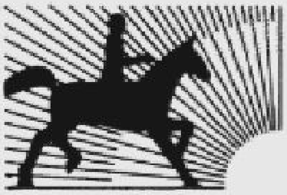

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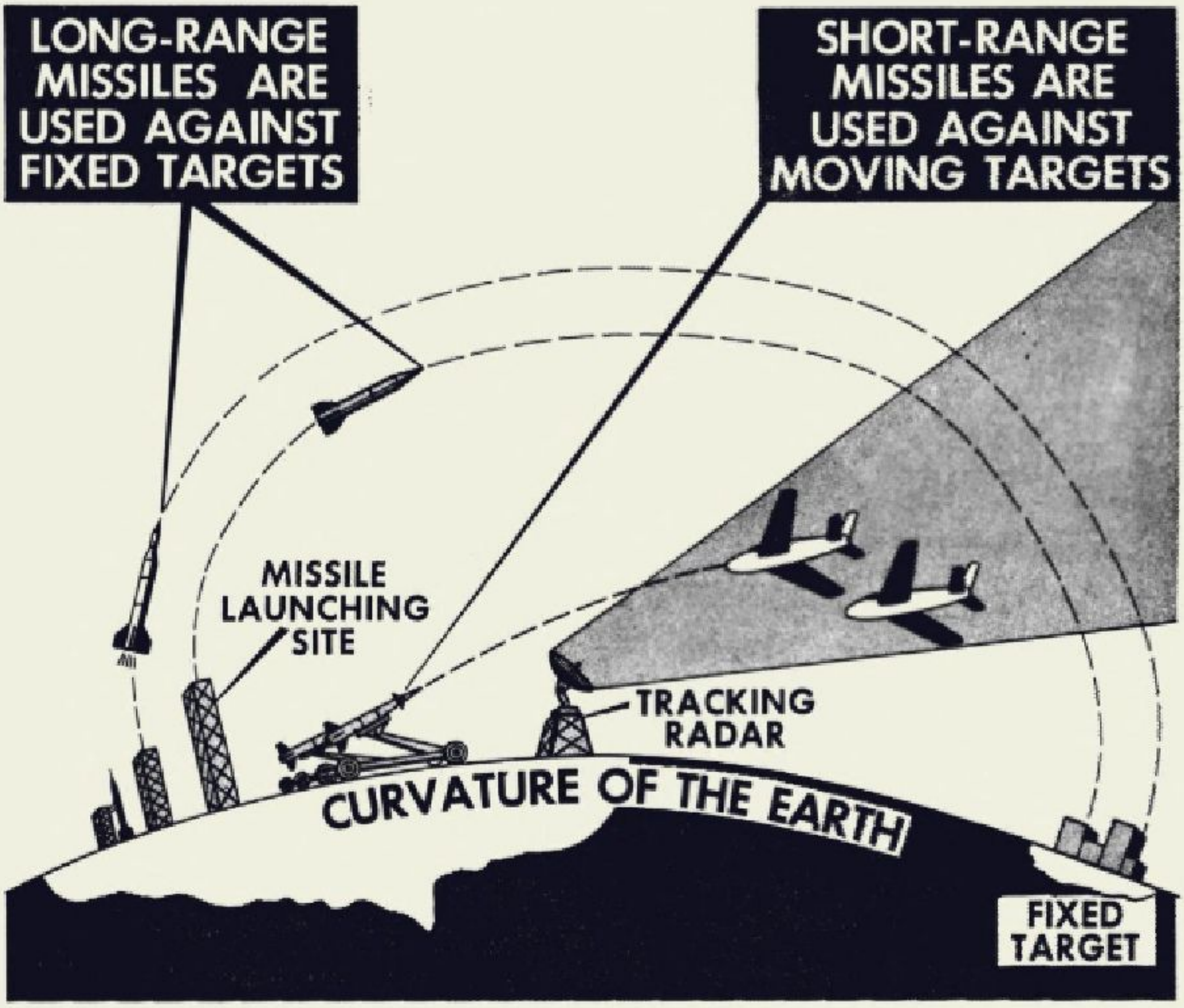
THE EVOLUTION OF GUIDANCE TECHNIQUES

Introduction to Missile Control and Guidance

In about two decades both short-range and long-range guided missiles have evolved from simple unguided rockets, autopiloted aircraft, and the basic radar systems for aircraft detection and tracking. Practically all types and ranges of missiles require guidance to be effective against either moving or fixed targets. (The term *fixed targets* means those fixed to the Earth. From a space viewpoint all targets are moving. For instance, while a ballistic missile is in flight the target at which it has been fired moves an appreciable distance because it is fixed to a rotating Earth.)


LONG-RANGE MISSILES ARE USED AGAINST FIXED TARGETS
SHORT-RANGE MISSILES ARE USED AGAINST MOVING TARGETS
MISSILE LAUNCHING SITE
TRACKING RADAR
CURVATURE OF THE EARTH
FIXED TARGET

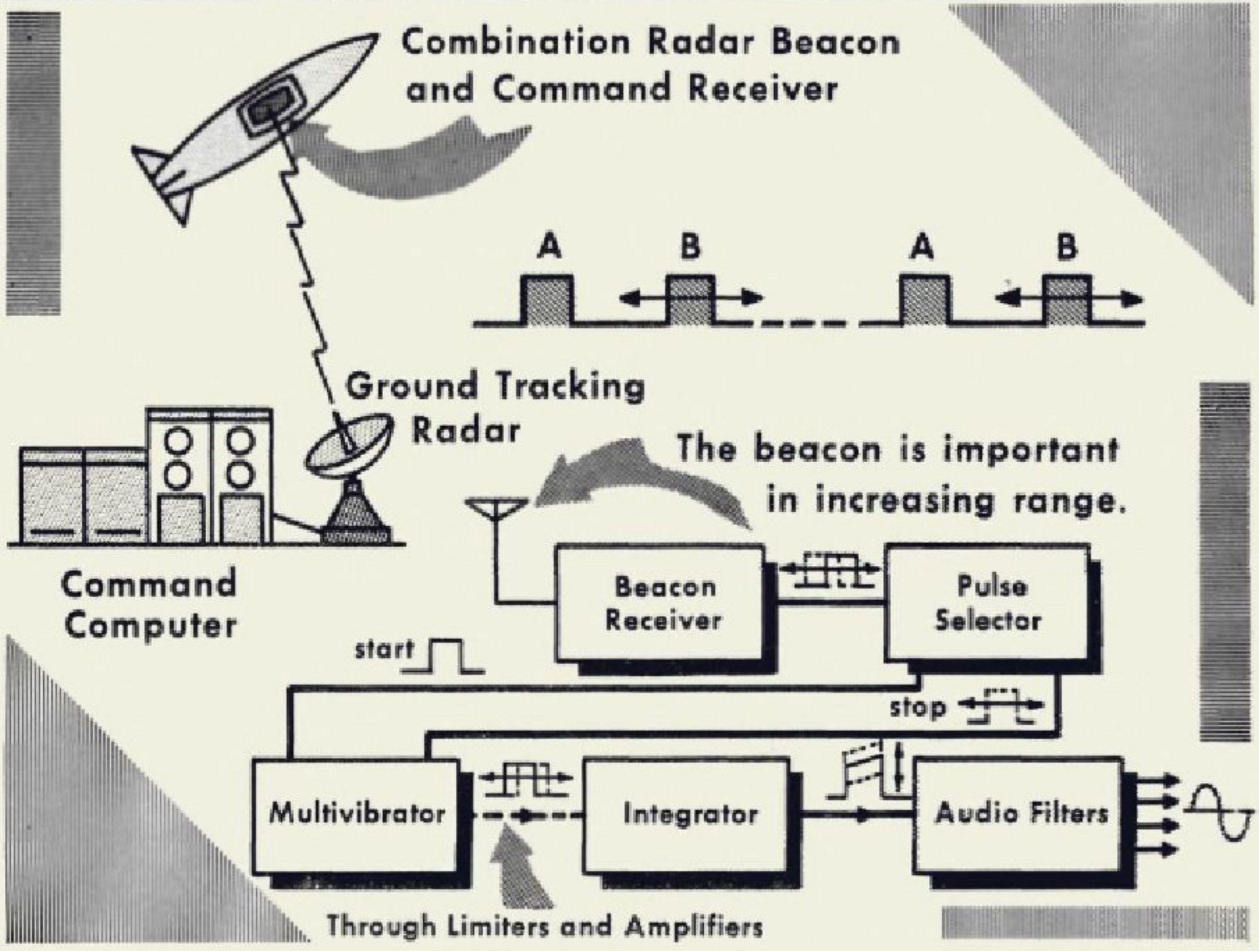
Long-range missiles are used against fixed targets over distances ranging from 200 to 5000 miles, and require a high order of navigational accuracy to insure that the error at the target area will not be excessive. Short-range missiles may be used against either fixed or moving targets in ranges less than 200 miles. Since most short-range missile applications are against moving targets, a high degree of target observation is necessary, and a rapid-action system for bringing the missile to bear on the target is essential.

Radar Command Guidance (contd.)

In a typical radar system, employing pulse modulation of the radar signal, a beacon is carried in the missile to enhance the return signal over that which could be realized with so-called *skin-tracking* by direct reflections from the missile's surface. The missile beacon responds only to a certain pulse combination from the ground radar and sends back a signal, which is tracked by the ground radar.

In addition to the tracking pulses the radar system transmits two additional pulses A and B. The latter pulse is shifted back and forth in position relative to pulse A in accordance with the amplitude of the command signal so that pulse position modulation is realized. When the pulse modulated signal is accepted at the beacon receiver it is used to trigger a multivibrator. The fixed pulse starts the multivibrator and the variable-position pulse stops it. Thus, pulses of varying width are generated. These are fed through an integrating circuit so that the square wave produces a signal with a sawtooth top. The amplitude variation of this signal can be filtered so that a sinusoidal voltage is developed for a control function of the missile.

Using the Radar Signal for Command Communication


Combination Radar Beacon and Command Receiver
A
B
A
B
Ground Tracking Radar
The beacon is important in increasing range.
Command Computer
Beacon Receiver
Pulse Selector
start
stop
Multivibrator
Integrator
Audio Filters
Through Limiters and Amplifiers

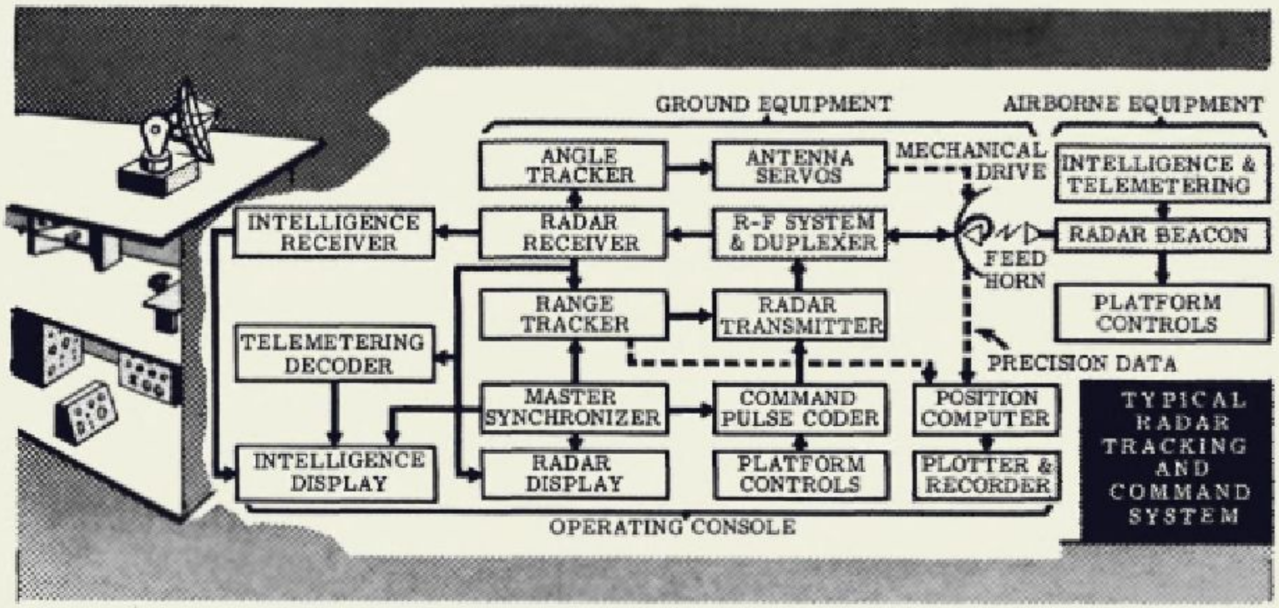
Modern Radar Systems

A typical present-day tracking radar is the AN/FPS-16, which was developed for guided missile test ranges. It is a monopulse type with a somewhat better accuracy than the conical scan radars previously employed.

A two-to-one improvement in range is also provided. The antenna system for this equipment consists of a four-horn monopulse feed. The AN/FPS-16 may be used as a path for two-way communications as well as for location purposes. In such an operation the radar transmitter interrogates a beacon in the missile, whose first response pulse is used to establish range and angle track by the radar. This signal keeps the radar antenna on the target and provides for a continuous position plot on the ground. The drone or missile may receive command guidance through additional pulse signals preceding the ranging pulse. They are coded to match the preset code in the beacon and pulse-position modulated to provide several channels of about 100 cycles bandwidth. As many as 10 or 20 separate pulses can be used, and the bandwidth can be utilized by frequency- or time-division to control several independent functions.

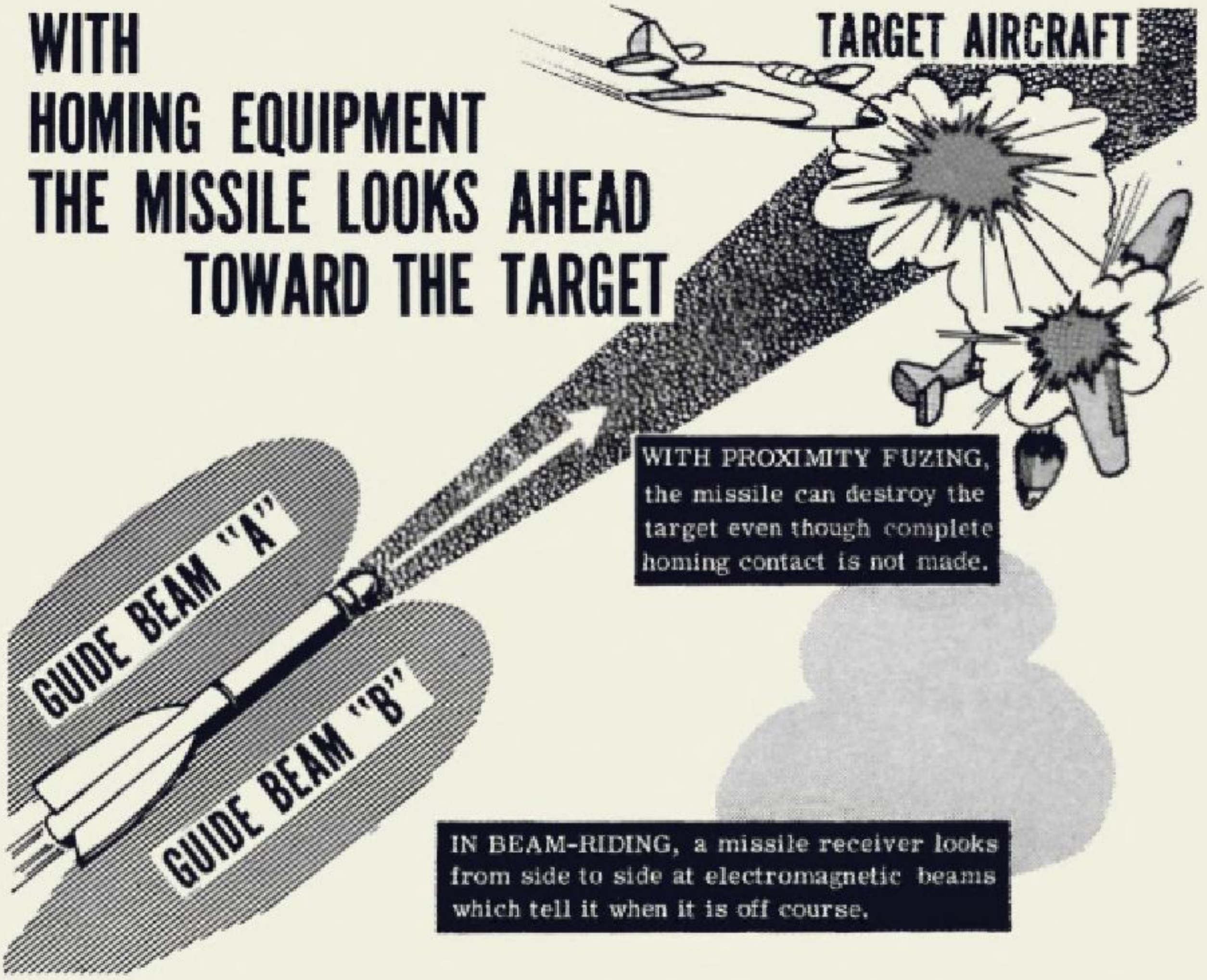
The following comparisons can be made between the AN/FPS-16 and the SCR-584 radar of World War II fame:

Characteristics	SCR-584	AN/FPS-16
Operating Frequency Band	S	C
Peak Power (kw)	250	1000
Antenna Size (diameter, feet)	6	12
Beamwidth (degrees)	4	1.2
Accuracy: Range (yards)	20	5
Angle (mils)	2	0.1



GUIDE BEAM, DOPPLER, AND HOMING TECHNIQUES

Introduction


WITH HOMING EQUIPMENT THE MISSILE LOOKS AHEAD TOWARD THE TARGET
TARGET AIRCRAFT
GUIDE BEAM "A"
GUIDE BEAM "B"

WITH PROXIMITY FUZING, the missile can destroy the target even though complete homing contact is not made.

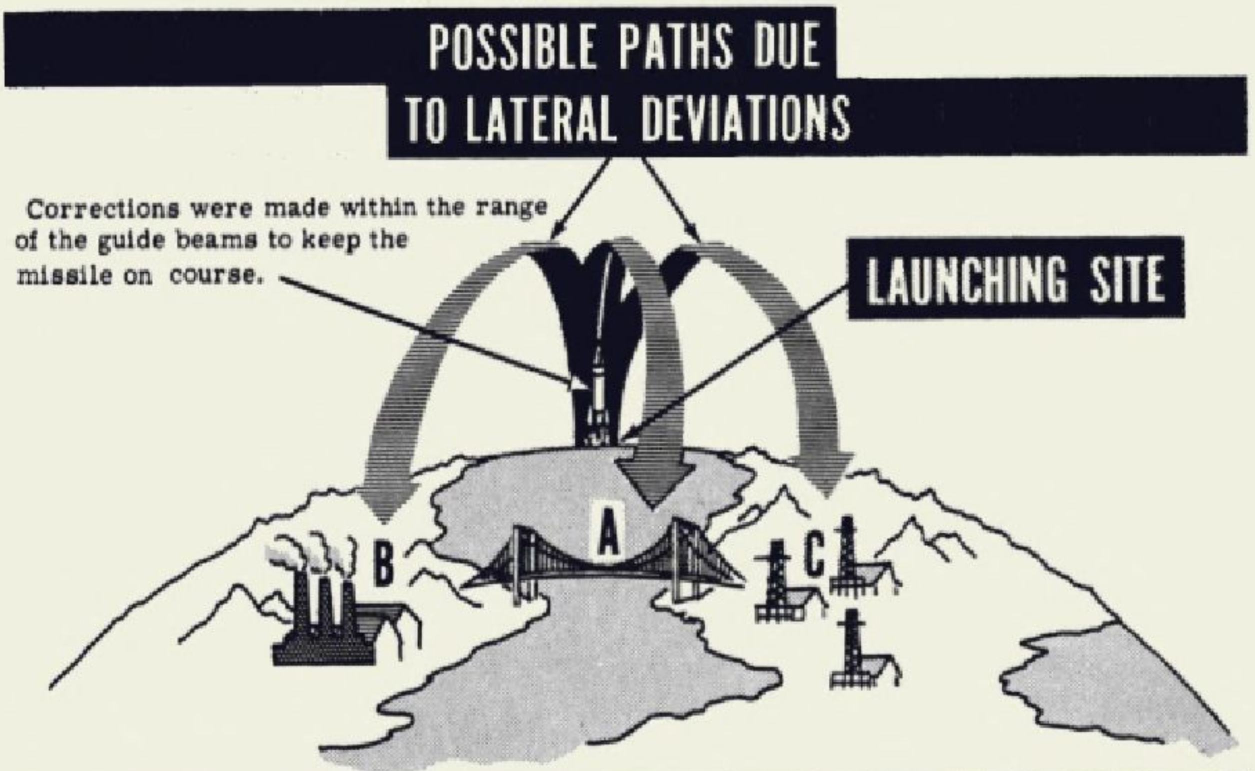
IN BEAM-RIDING, a missile receiver looks from side to side at electromagnetic beams which tell it when it is off course.

Previously we dealt with radio and radar methods of providing guidance from sensing devices external to the missile. We shall now deal primarily with radio, radar, and infrared techniques for providing guidance from sensing arrangements within the missile. Later we shall consider internal techniques which employ celestial and inertial sensors. Guide beam, homing, and proximity applications were developed to some degree during World War II. Since that time they have been improved extensively for defensive missiles operating against moving targets — particularly high-speed aircraft.

In the future, further developments especially in homing techniques are indicated in the solution of antimissile defense problems as well as space rendezvous between orbiting vehicles. Homing and proximity techniques may be applied independently or in conjunction with other basic forms of guidance, such as command systems. For example either guide-beam or command techniques may bring the missile onto the proper course with the principal application of homing and/or proximity fuzing as the missile comes into close range of the moving target.

Beam-Riding Guidance

Missiles utilizing guide-beam information to establish their correct position relative to a target area are called *beam riders.* They may be launched either from surface bases or an aircraft, and require that a radio system capable of establishing a guide path, or a radar capable of tracking a target, be available to establish a suitable radiated signal-pattern in which the missile can travel toward the target. The missile contains a receiver for detecting deviations from the proper position in the guide-beam pattern, and from this data establishes the proper flight path without any command signals from the guiding source.


POSSIBLE PATHS DUE TO LATERAL DEVIATIONS
Corrections were made within the range of the guide beams to keep the missile on course.
LAUNCHING SITE
A
B
C

Under autopilot control, the V-2 ballistic missile might deviate laterally either to the left or right, causing it to impact at points B or C, rather than at A.

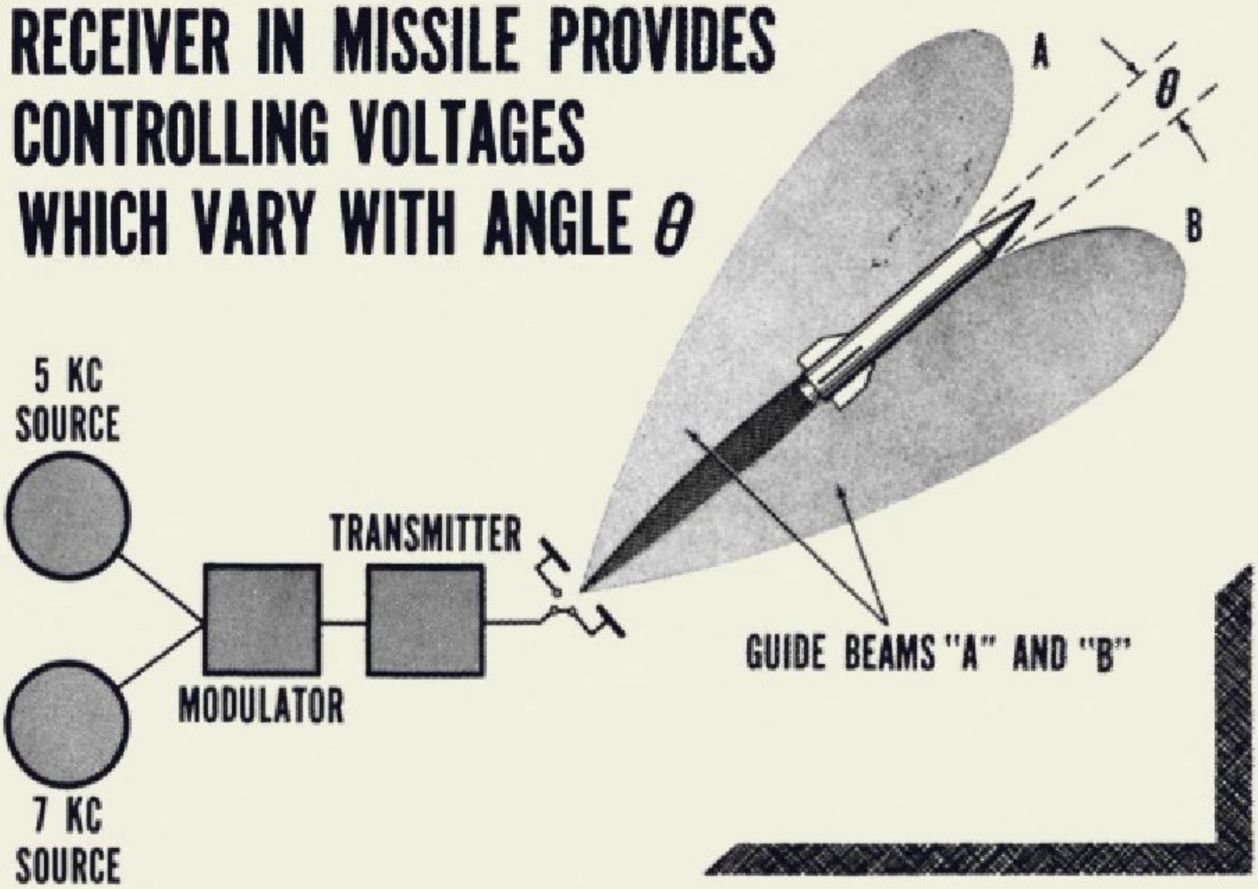
One of the earliest applications of the guide-beam technique was made during World War II in V-2 guidance utilizing a radio technique, similar to that developed in the mid-1930s for the blind landing of aircraft. Although the Germans often employed a self-contained nonradiating form of inertial guidance for many V-2 launchings, especially when the jamming of radio or radar signals appeared likely, they also developed, and sometimes employed, a radio guide-beam system to correct for lateral deviations from the desired path. With this method they obtained greater accuracy at the target. However, inertial guidance was not fully developed for higher accuracies at that time, so a comparison of guide beam versus inertial guidance would not necessarily be the same today as it was in World War II.

Beam-Riding Guidance (contd.)

In the missile application the blind landing technique was essentially reversed to place an object into a position above the ground rather than on a landing strip. In the V-2 guide-beam system a ground-based transmitter, operating at about 50 mc, was positioned at a distance of about 6 miles behind the launching site. The transmitter fed two horizontal dipoles positioned at a distance of about 600 feet from each other. This feed was alternated between the two antennas at a switching rate of 50 cycles and the beam characteristics *a* and *b*, were obtained alternately.

The signal was also modulated by two additional audio signals — 5000 cycles in beam *a* and 7000 cycles in beam *b*. When the missile was to the left of the desired course, the 5000-cycle modulation predominated at the missile receiver. When to the right of the desired course, the 7000-cycle modulation was the stronger. The signal received at the missile was demodulated down to the 50-cycle modulation. The resulting envelope was passed through a filter for that frequency. At the receiver output in the V-2 rocket a voltage was obtained whose positive or negative sign depended upon the lateral position (right or left) of the rocket, and was proportional to its angular position Θ.

This guide-beam system was developed for 10 different radio frequencies to avoid interference from countermeasures.



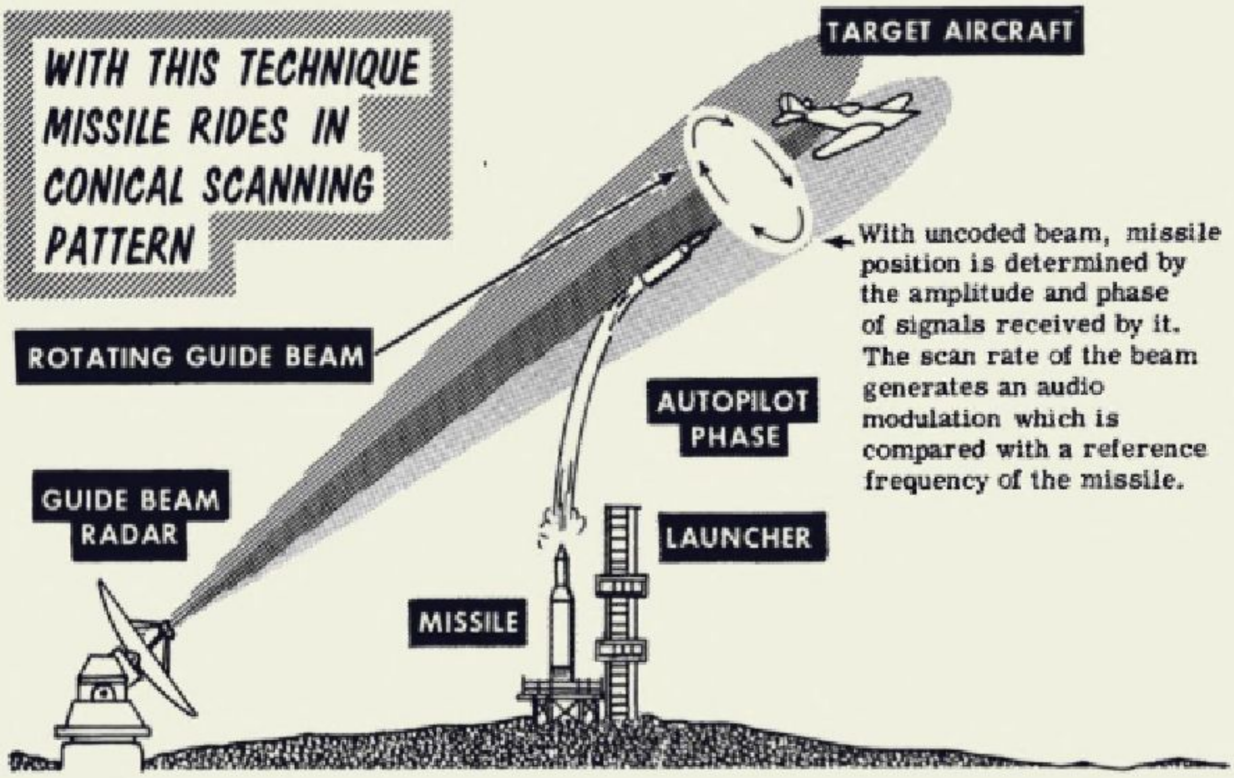
RECEIVER IN MISSILE PROVIDES CONTROLLING VOLTAGES WHICH VARY WITH ANGLE θ

Radar Beam-Rider Guidance

In the application of the beam-rider technique to systems employing radar tracking of a target, the initial guidance phase must depend upon an autopilot in the missile to keep it in a position where it can be captured by the guide beam. However in this technique the guiding radar equipment must provide two essential elements to the missile; (1), the required course to the target, and (2), a reference which enables the missile-circuits to measure the weapon's position in space with respect to this course.

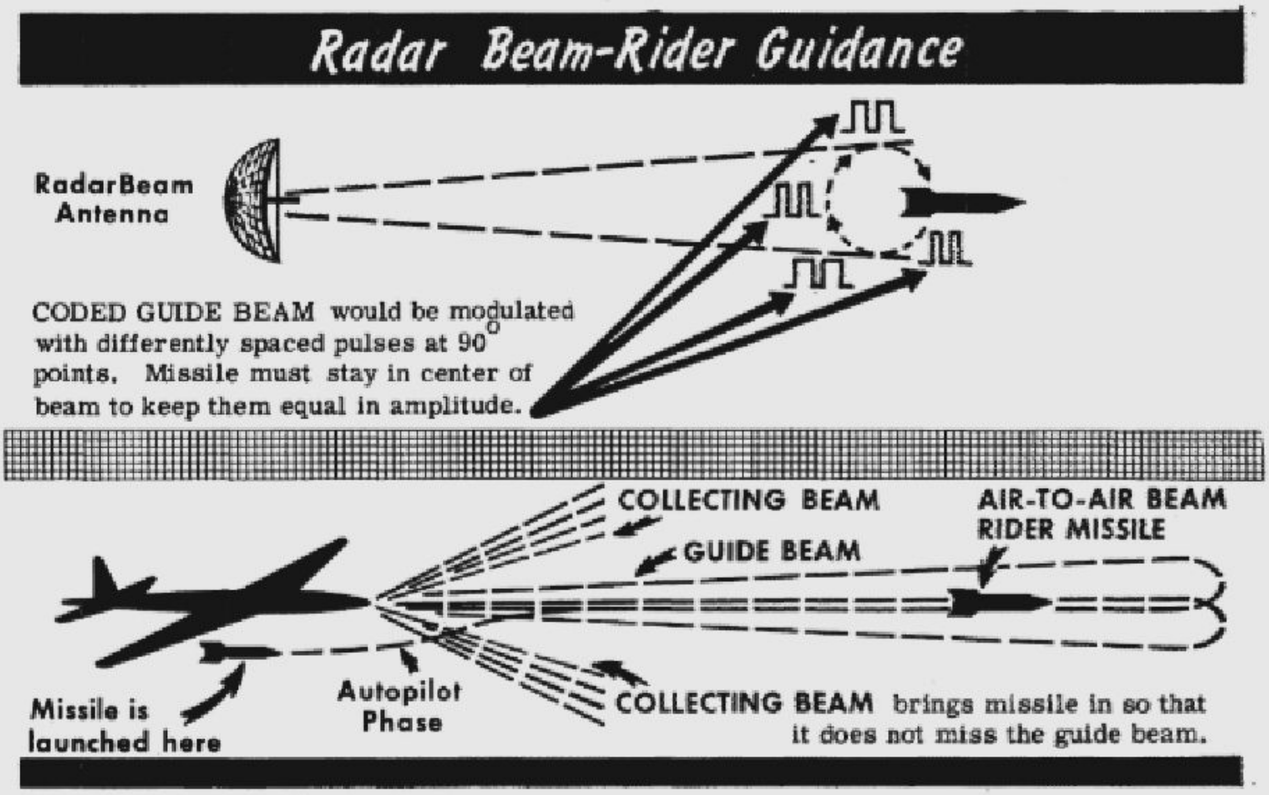
The path along which the missile must fly is defined by the tracking operation of the radar. Prior to launching and throughout the boost phase of the missile, the beam-radar antenna is directed automatically so that the center of its radar-beam pattern points to the target. The second element that enables the missile to determine its position in space relative to the target is provided by guidance signals from the beam received at the missile.

The beam is rotated in a conical pattern in space to give position information to the missile receiver. By demodulating the signal from the radar beam, which is rotated at a low audio rate from 50 to 75 cycles, we may determine the deviation of the missile from the center of the scan pattern by determining the amplitude of the scanning-rate signal. By making a phase-comparison between an audio reference signal in the missile and the scanning signal, it is possible to determine the angular displacement of the missile around the beam-pattern. By applying these deviation signals through the proper control-channels the missile can be brought back to the center of the conical beam and into the correct direction toward the target.



With uncoded beam, missile position is determined by the amplitude and phase of signals received by it. The scan rate of the beam generates an audio modulation which is compared with a reference frequency of the missile.

Radar Beam-Rider Guidance (contd.)



CODED GUIDE BEAM would be modulated with differently spaced pulses at 90° points. Missile must stay in center of beam to keep them equal in amplitude.

COLLECTING BEAM brings missile in so that it does not miss the guide beam.

Another method of determining the missile's position in the conical scan pattern is to place a pulse code on the radar signal. With this method pulses of varying spacing are placed at 90° intervals around the circle described by the conical scan. By comparing the intensity of these pulses in the missile receiver it is possible to provide control voltages which will send the missile *up* or *down* or to the *right* or *left* to bring it into the center of the conical scan pattern. Although a beam-rider missile depends upon its autopilot to establish its course during the launching phase, it can be brought under control at an early stage in its flight path by providing a *collecting* radar beam in addition to the normal conical-scanning radar beam. This beam subtends a somewhat wider angle, and can be picked up by the missile receiver closer to the launching point than the narrow guide-beam. After receiving the *collecting* signal the missile will intercept the guide-beam as it travels toward the target.

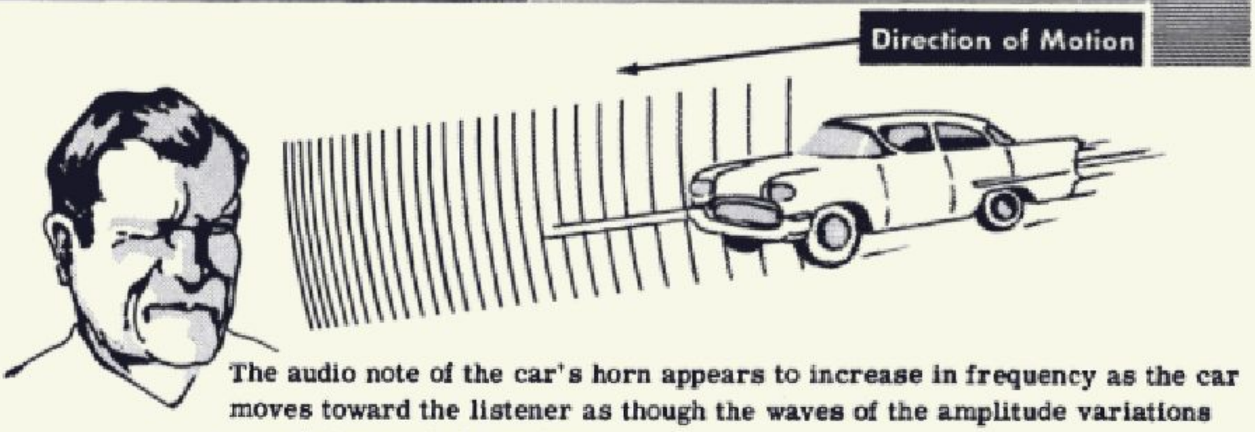
Another refinement of the beam-rider system is sometimes employed. A separate radar equipment tracks the target, and provides follow-up information to the guide-beam radar. This method is more applicable to surface-launched missiles, where excessive maneuvering at low altitudes might be required in a single beam system.

Single radar guide-beam systems have been used for air-to-air missiles. In this case several missiles, fired in sequence, can be guided by one radar. If they are spaced by a slight time interval, no difficulties should be encountered.

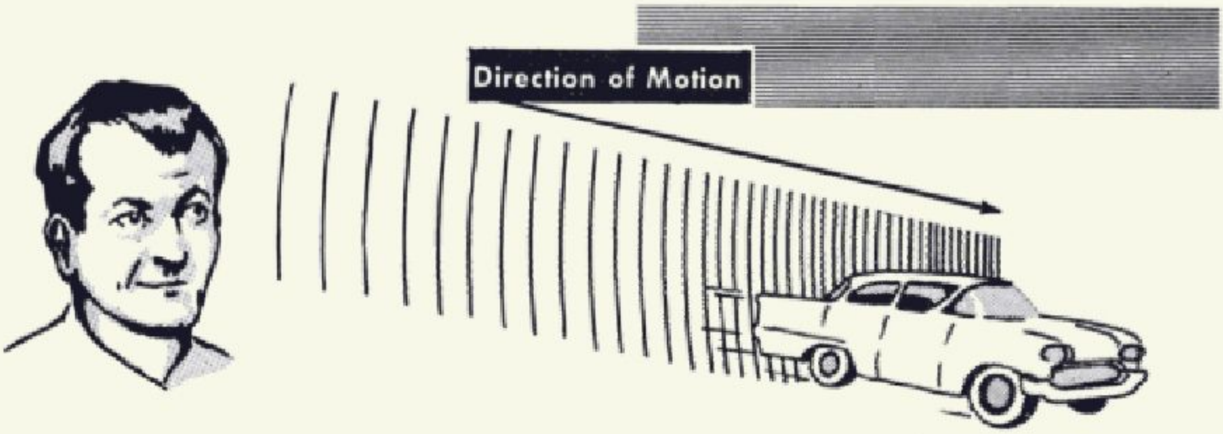
Doppler Principles and Applications

For navigation and homing purposes it is often advantageous to employ CW radar. The Doppler shift of frequency offers a medium for extracting information from a CW system. A common effect in nature is demonstrated every day of our lives by the change in pitch of horn signals and whistles from moving vehicles, such as autos and railroad engines. The pitch of the sound is shifted from that present when the vehicle is stationary with respect to the listener. This principle is named for Christian Johann Doppler, who stated in 1842 that "If the distance between an observer and a source of vibration is changing the frequency of vibrations appears to become greater or smaller than the true value — depending on whether the distance is being diminished or increased." By utilizing this principle, the velocity of an object relative to that of a source of vibrations can be determined, if a comparison is made between the frequency of the fixed source and the apparent frequency of the vibrations at the object in motion.

THE DOPPLER EFFECT



The audio note of the car's horn appears to increase in frequency as the car moves toward the listener as though the waves of the amplitude variations were being pushed together.



The audio note of the car's horn appears to decrease in frequency as the car moves away from the listener as though the waves of the amplitude variations were being pulled apart.

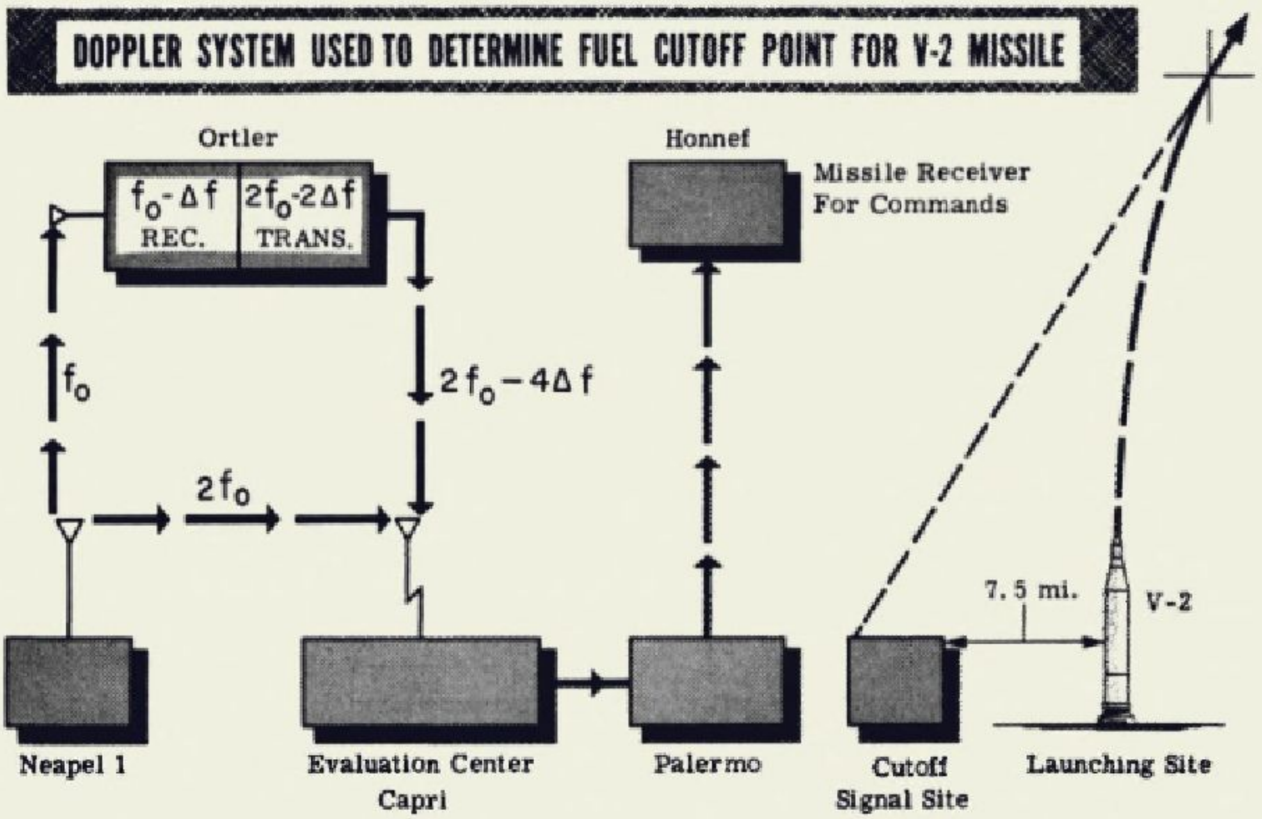
Doppler Principles and Applications (contd.)

Using the *Wolmann Cutoff* method (named for Dr. Wolmann of Dresden) the Doppler effect was employed to measure the velocity of the V-2 missile and to determine the point in the trajectory at which its rocket thrust should be throttled back and cut off.

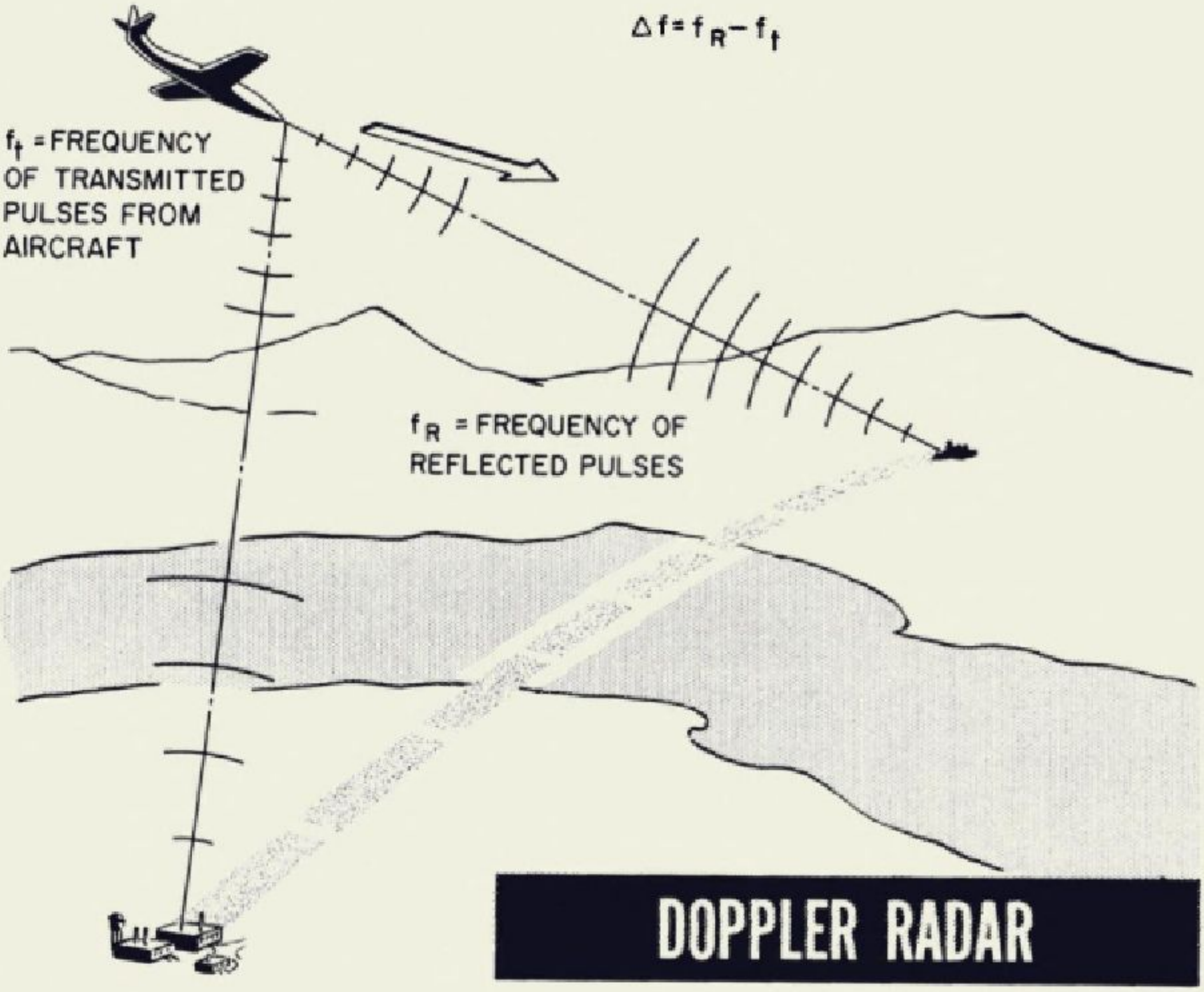
Using the code words of that era the operation of the *Wolmann* system may be described as follows: A ground-transmitter, *Neapel I*, emitted a signal of frequency f_0. A receiver in the missile, *Ortler*, received the frequency $f_0 - \Delta f$ (Δf being the change due to the Doppler shift). To avoid interference with the *fundamental* transmission frequency, and improve the accuracy of the system, the frequency was doubled at the missile before sending it back to the ground evaluation center, *Capri*. Of course it was received back at that point with a further Doppler shift to provide a total signal-frequency of $2 f_0 - 4 \Delta f$ for comparison with the second harmonic, $2 f_0$.

When the frequency shift indicated the proper velocity for fuel cutoff at V-2, a command-signal was sent through the radio transmitter, *Palermo*, to a radio receiver, *Honnef*, in the missile to produce the desired reduction in thrust, which was accomplished in two stages; first, a cutback from 25 tons to 8 tons thrust and second, a complete thrust cutoff 3 seconds later. This method was just one of the techniques employed for controlling the fuel cutoff of the V-2. Another method used more often involved self-contained integration of acceleration to determine the proper point to reduce the thrust.

DOPPLER SYSTEM USED TO DETERMINE FUEL CUTOFF POINT FOR V-2 MISSILE



Doppler Principles and Applications (contd.)


$\Delta f = f_R - f_t$
f_t = FREQUENCY OF TRANSMITTED PULSES FROM AIRCRAFT
f_R = FREQUENCY OF REFLECTED PULSES

DOPPLER RADAR

Since that time applications of the Doppler principle have been developed for altimeters, airborne-radar systems, and homing heads. In these applications reflected waves are compared with the incident waves with regard to frequency shift. Since reflected signals are utilized for comparison purposes, all of these systems are considered to be in the radar family. The mathematics for determining the shift frequency is fairly simple. If an object at A radiates a signal of frequency f_t and if the signal is reflected from a moving object B, returning to A for comparison, the formula for the frequency shift is:

$$\Delta f = \frac{2V}{c} \times f_t$$

where c is the velocity of propagation of the electromagnetic signal and V is the velocity of B with respect to A. If A is moving relative to B at an angle, then the above quantity must be multiplied by the cosine of the angle to obtain the correct value.

Doppler Principles and Applications (contd.)

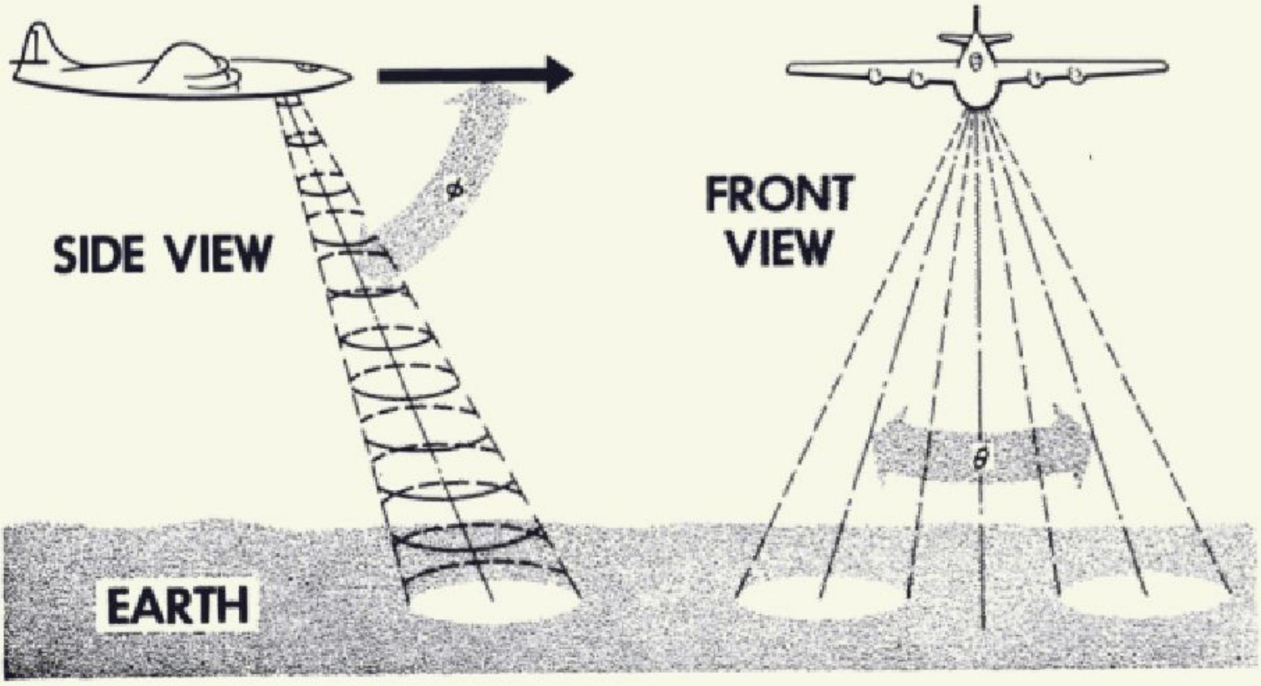
In the Doppler application to altimeters an FM technique is used to continually measure the frequency shift between the transmitted and reflected signals as received in the aircraft. Thus, even when the aircraft is moving at a constant distance with respect to the earth, the altitude will be indicated by the frequency comparison. Also, any change in altitude will be indicated in a Doppler shift of the frequency. A rather popular application of Doppler principle today is embodied in what is known as the *Doppler Navigator.* It may be applied to either aircraft or missiles. In its operation two beams are transmitted from the aircraft to the ground at the angle ϕ. As mentioned above the formula for Δf under these conditions would be:

$$\Delta f = \frac{2 V_g}{c} \times f_t \times \text{cosine } \phi$$

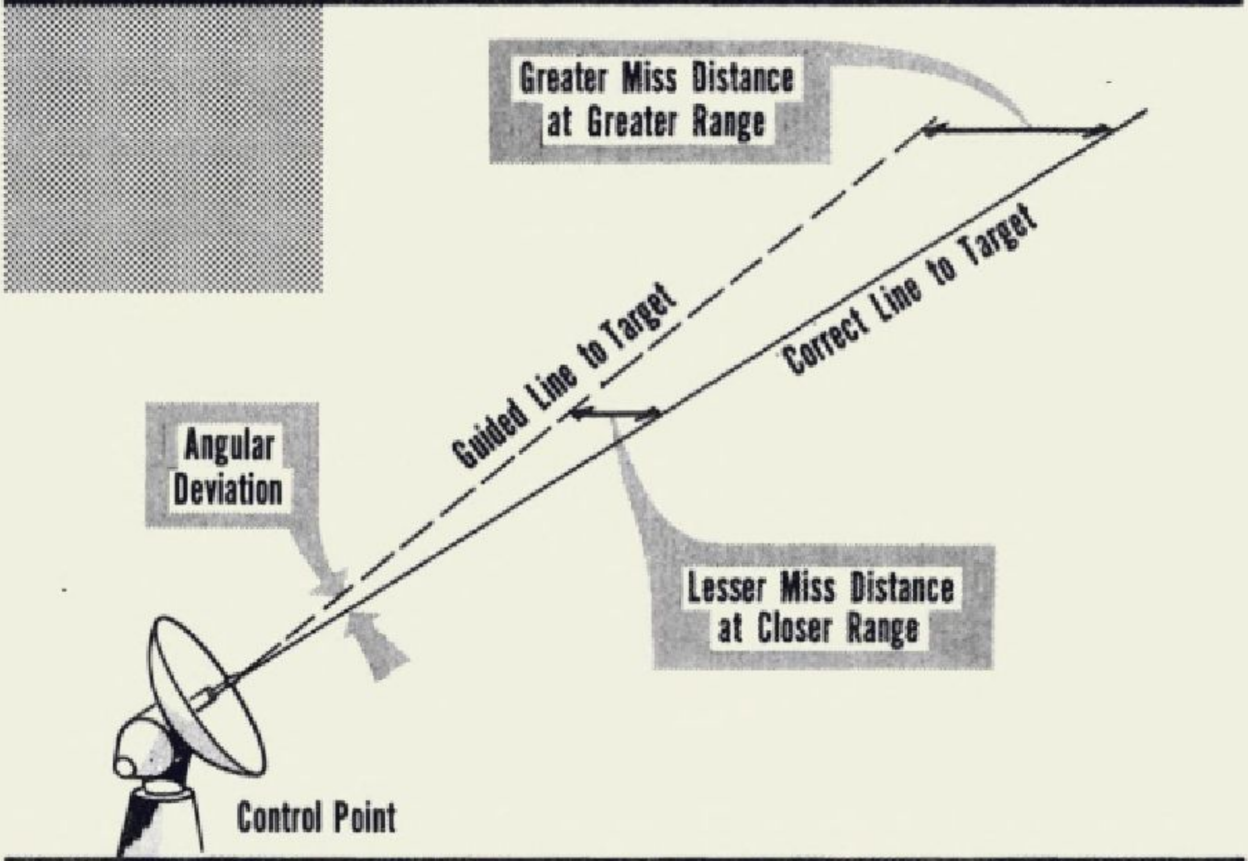
where V_g is the velocity of the aircraft relative to the ground.

By using the two beams it is possible to determine the ground speed of the aircraft by the measurement of Δf and it is also possible to determine the drift angle from a desired heading by rotating the two-beam antenna system until equal Doppler frequencies are received from one beam and noting the required angle of rotation to achieve this equality. Drift angle can also be determined with a fixed two-beam system by measuring the Doppler-frequency shift associated with each antenna-beam and calculating the drift angle corresponding to such a difference in Doppler shift.

DOPPLER APPLICATION TO NAVIGATOR



Missile Homing Methods


Greater Miss Distance at Greater Range
Guided Line to Target
Correct Line to Target
Angular Deviation
Lesser Miss Distance at Closer Range
Control Point

Range Proportionality of Command and Beam-Rider Systems Emphasizes the Need for Target Homing Devices in the Missile

Doppler systems may be operated with either continuous-wave (CW) modulation or with forms of pulse modulation. The type of modulation will depend somewhat on whether short- or long-range operation is desired.

When an air-defense missile approaches the target its ability to achieve an effective contact can be greatly enhanced by the addition of homing techniques. This situation is due in a large measure to the fact that both command and beam-rider guidance systems are subject to angular inaccuracies which make them range-proportional; that is, as the range increases the missile error relative to the target in distance also increases.

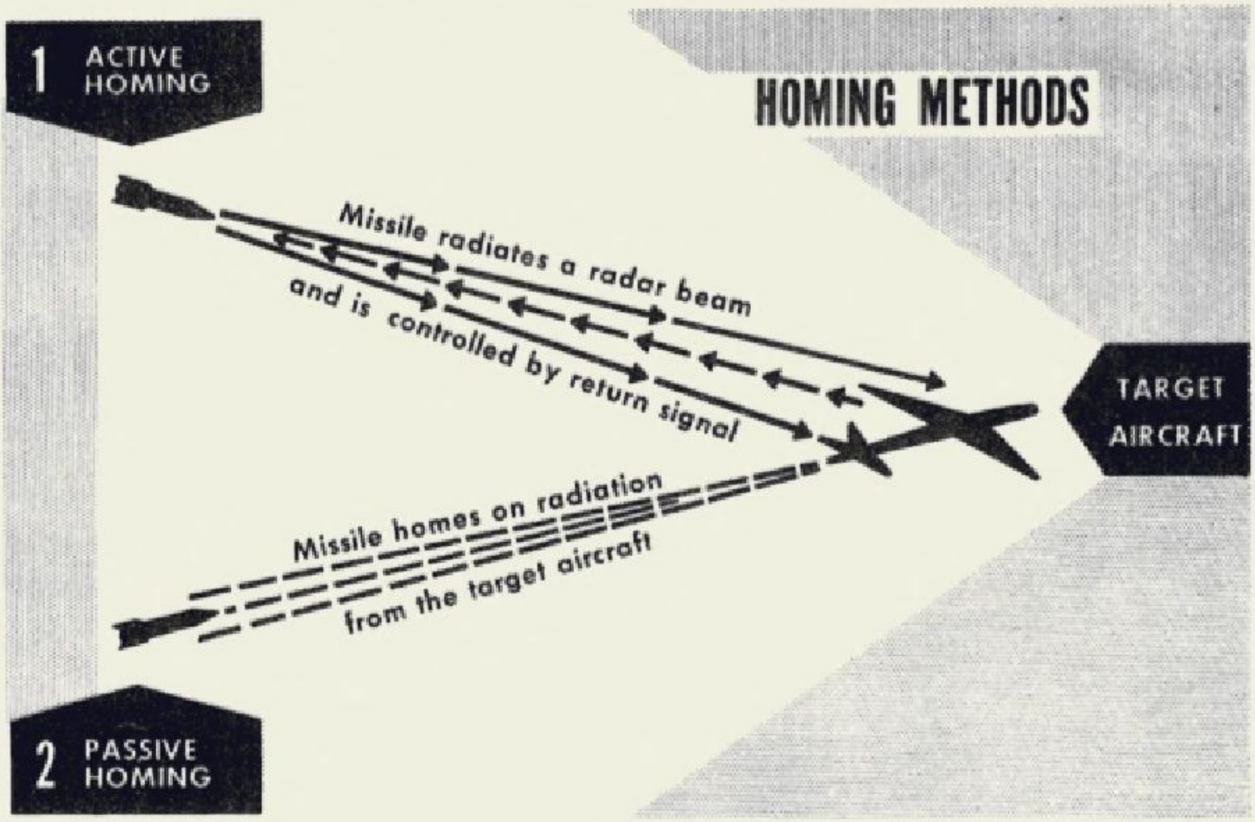
As the missile travels away from a ground-control point the deviation from the correct line to the target is proportional to the distance from the control point for any given angular deviation. By adding a target-homing guidance in the missile it is possible to reverse the situation so that as the missile approaches the target, from which it is deriving the homing signal, the angular deviation results in a decreasing distance-deviation.

Missile Homing Methods (contd.)

Although they used practically none of them, due to their deteriorating general conditions in the latter part of World War II, the Germans had under development a number of homing systems for surface-to-air, air-to-surface, and air-to-air missiles. They investigated electromagnetic, optical, infrared, and acoustical devices. However, most of their effort was concentrated on electromagnetic and infrared types. They felt that homing devices were the right approach for guiding a missile during the last phase of its flight path. Although they had under development a number of homing systems, which we shall describe briefly, they were farther along with infrared homing-development near the end of the war.

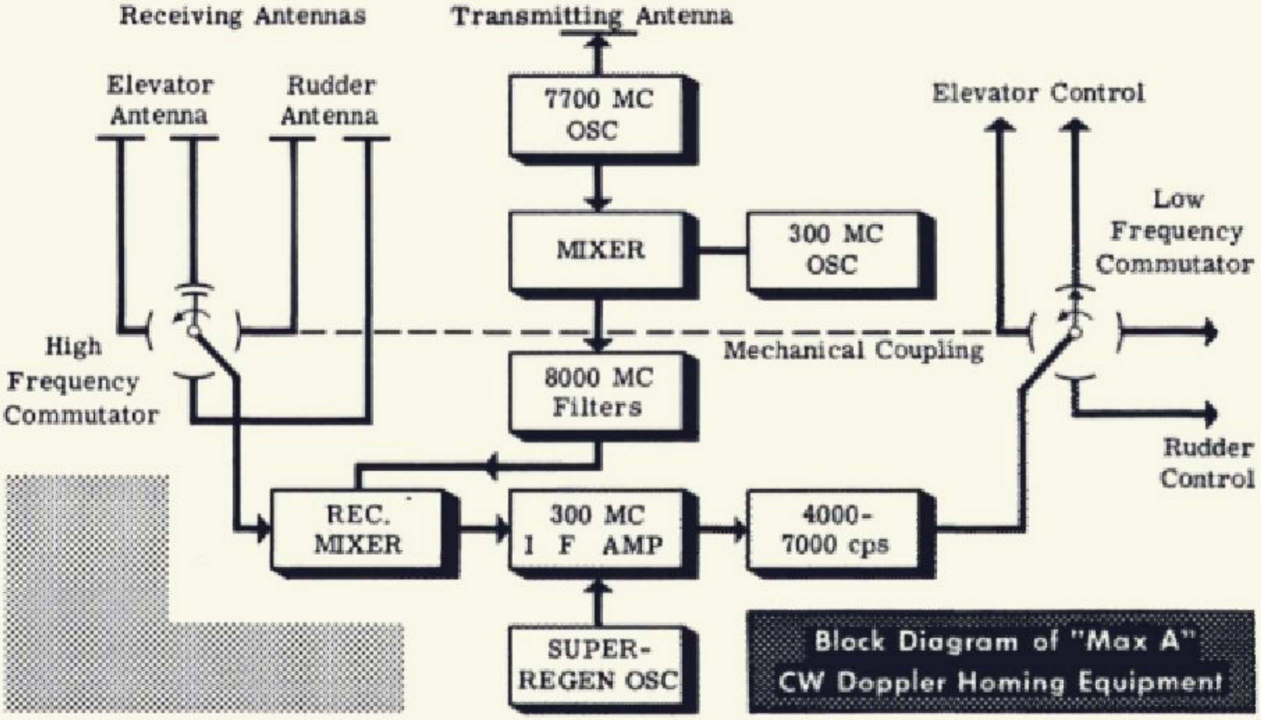
Earlier we mentioned three classes of homing systems — active, semi-active, and passive types. It will be recalled that with the active method, a signal is radiated from the missile and a reflected signal is received in return at the missile for determining the correct action to obtain a homing course to the target.

In the semi-active type the target is *illuminated* by a radar external to the missile which contains a receiver for detecting the reflected signal from the target. In the passive type radiated energy from the target is used as a source for exciting the receiver at the missile, causing it to take a path toward the target. This energy might be in the form of radiation from a radar in an attacking aircraft, from the heat of its engines, from the noise of its motors or from its light image.


1 ACTIVE HOMING
HOMING METHODS
Missile radiates a radar beam
and is controlled by return signal
TARGET AIRCRAFT
Missile homes on radiation
from the target aircraft
2 PASSIVE HOMING

Missile Homing Methods (contd.)

The following details on German equipment under development at the end of World War II — *Max A*, *Max P*, and the *Moritz* systems — illustrate the principles of active, passive and semi-active systems:



Block Diagram of "Max A" CW Doppler Homing Equipment

The transmitter of *Max A* radiated approximately 5 watts of CW power from a horn antenna at 7700 mc. This signal was obtained from an 8-slot magnetron working with a plate voltage of 600 volts and a field intensity of 1000 gauss. Since the received signal from the target would be shifted only a few thousand cycles away from the transmitted frequency due to the Doppler effect, it was necessary to eliminate the frequency-drift effects in the receiver.

A high order of stability was realized by beating a voltage from the transmitter with a frequency-stabilized oscillator at 300 mc within the Max A equipment. By selecting the sum frequency through a filter system, a local oscillator frequency of 8000 mc was available at the receiver to beat with the reflected signal from the target. This mixing action produced an intermediate frequency of 300 mc from which the 4000 to 7000-cycle Doppler-shift audio signal was detected to provide control signals to the elevator and rudder of the homing missile.

Designs were provided for both fixed and movable antennas. The voltage difference of the rudder and elevator-antenna sections was used to correct the course of the missile until the signal from the target was in the plane of symmetry of both the horizontal and vertical arrays.

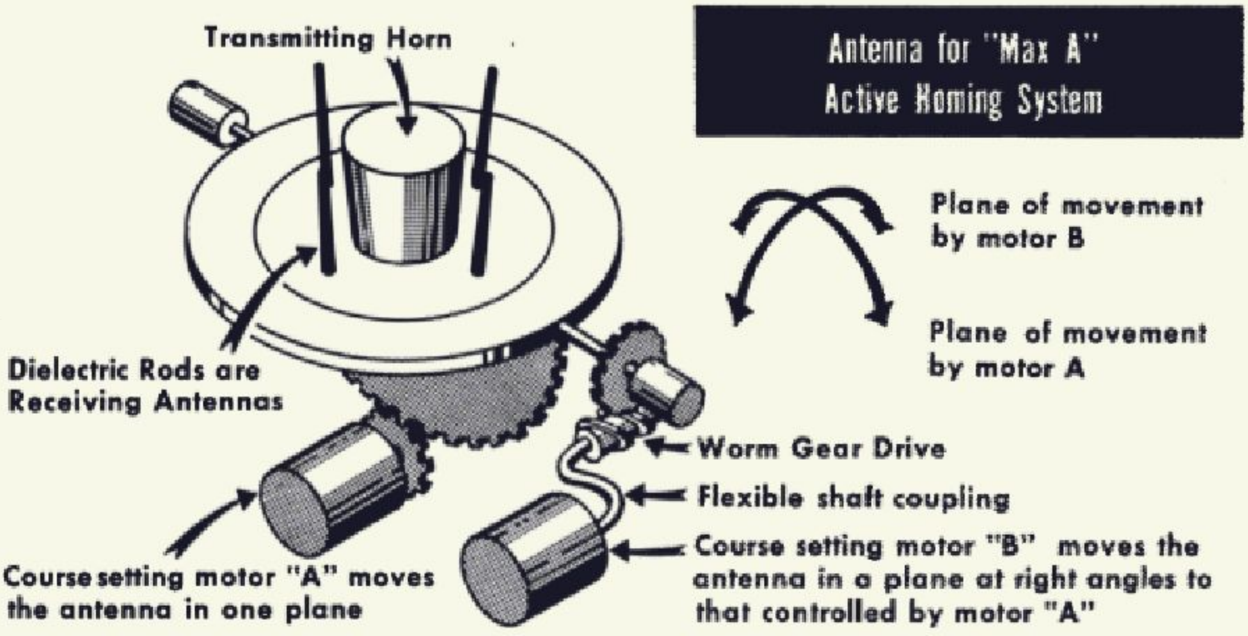
Missile Homing Methods (contd.)

The receiver antenna was constructed of dielectric rods with a half-lobe angle of 15°. In the case of a 1° displacement of the target, the deviation of the receiver antenna from its 15° mean position produced sufficient change in the receiver output to operate the differential relays and to change the course of the missile.

In order to produce better decoupling, the transmitter antenna was constructed as a horn of sheet metal. Two antenna arrays were employed for different homing approaches: a rigid antenna head, fixed on the axis of the missile for pursuit courses, and a movable antenna for collision courses. The pursuit course was planned for air-to-air operations, and the collision course for ground-to-air use. When operating with the collision-course system, it was necessary to guide the missile from the ground until it came within the range of its own self-contained homing device.

After locating the target, the seeking head in the first stage of the array automatically turned itself toward the target without affecting the navigation of the missile. Upon reaching a distance of approximately 3000 feet from the target, the angle between the axes of the missile and the antenna head was fixed, and automatic navigation was begun with the aid of a potentiometer. The head turned in the direction of the target, moved the potentiometer, and disturbed the balance of a resistance bridge, which altered the course of the missile until the fixed angle between the array head and the missile axis was obtained.

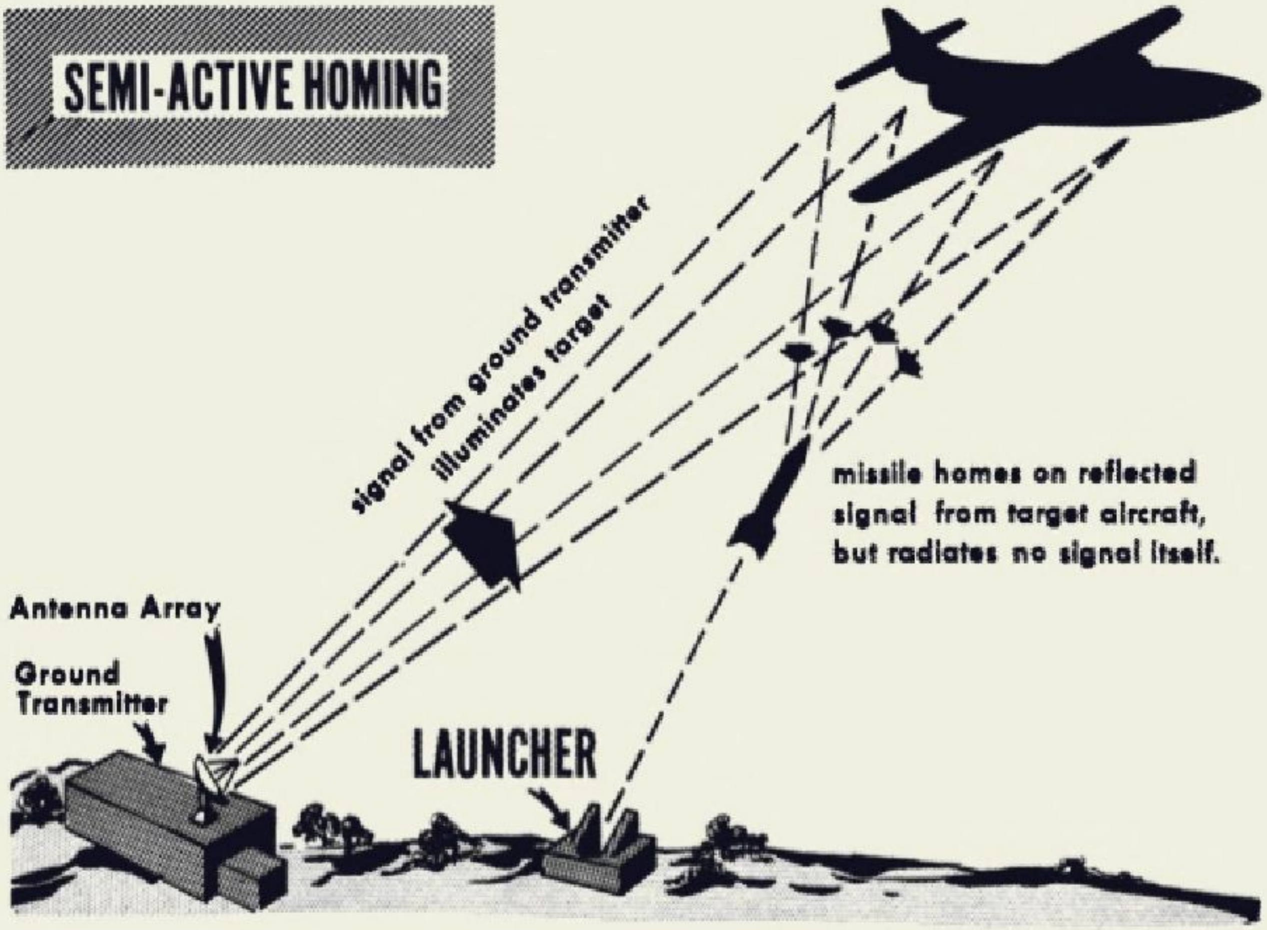
The movement of the antenna was produced by two course-setting motors — one moved the antenna drive directly, and the other produced the rectangular movement through a flexible shaft. Thus it was possible to set the antenna to any direction in space.



Antenna for "Max A"
Active Homing System

Transmitting Horn
Plane of movement by motor B
Plane of movement by motor A
Dielectric Rods are Receiving Antennas
Worm Gear Drive
Flexible shaft coupling
Course setting motor "B" moves the antenna in a plane at right angles to that controlled by motor "A"
Course setting motor "A" moves the antenna in one plane

Missile Homing Methods (contd.)


SEMI-ACTIVE HOMING
signal from ground transmitter illuminates target
missile homes on reflected signal from target aircraft, but radiates no signal itself.
Antenna Array
Ground Transmitter
LAUNCHER

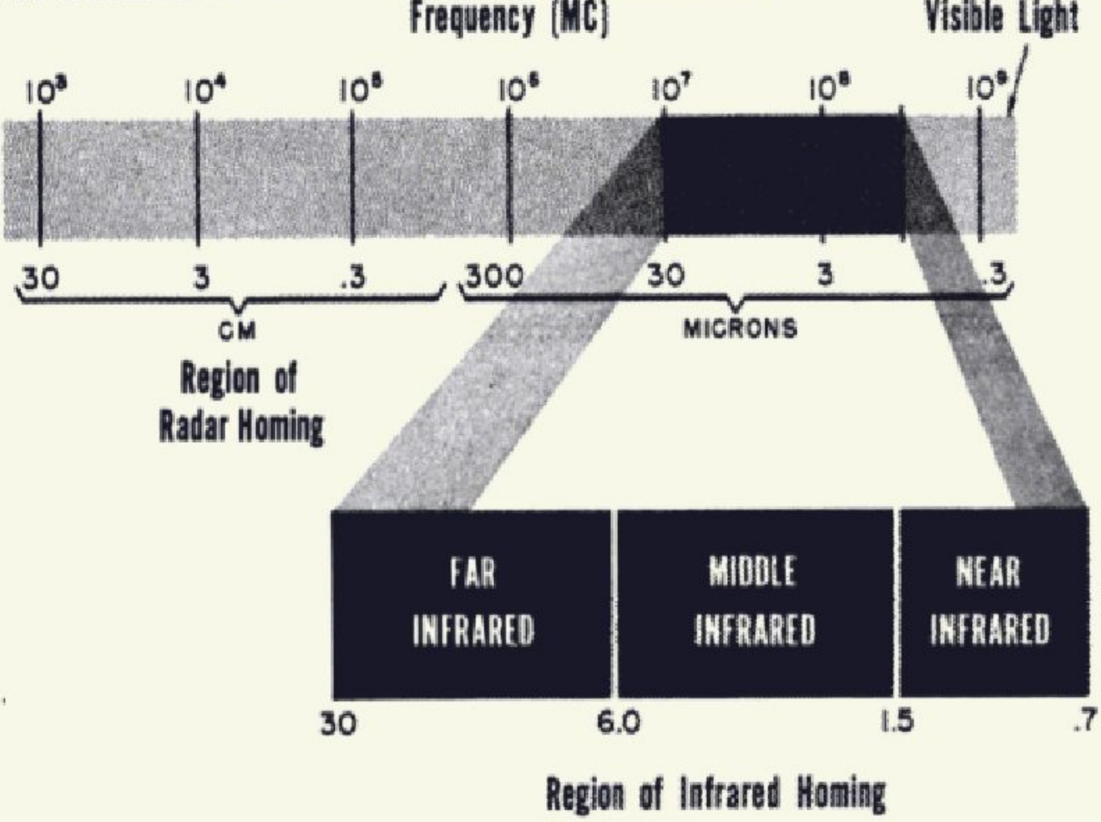
The *Max P* passive homing system was constructionally similar to the *Max A* active homer, except that the transmitter was not included. It homed on the radar emissions of hostile aircraft and it is said that ranges of up to 30 miles were obtained against 3-cm airborne radars. However, a major difficulty was experienced in the long time interval of 2 to 3 seconds between the radar signal sweeps across the missile. Because of this no homing information was available to this passive system during relatively long intervals of time.

The *Moritz* system serves to illustrate the semi-active homing application. The transmitter, which had a CW output of 10 watts, was located on the ground instead of in the missile. Although it operated at a somewhat lower frequency (430 mc), than *Max A* or *Max P*, it made use of the Doppler effect between the direct wave and the reflected wave and navigated on the latter. This system had advantages of small weight and low cost in so far as the missile was concerned, since the transmitter was located on the ground, and no need for direct coupling between the transmitter and the receiver. However, the missile could, unless carefully launched, attack the ground transmitter instead of the target. Also the ground transmitter could be located and knocked out by enemy action. The details of present-day homing systems for missiles are classified by military security regulations.

Infrared Homing Techniques

World War II saw the start of the initial development of infrared homing systems for missiles to be launched against targets with heat radiation as the detectable quality. In Germany basic laboratory investigations to determine the feasability of using infrared radiations for military purposes started in the early 1930s. Both active and passive systems appeared to be feasible, but the simplicity of the passive systems presented the greatest attraction. The heat radiation from the exhaust gas of reciprocating engines appeared adequate, and without the need of any active means for *illuminating* the target. With the advent of jet engines and rockets the heat radiation from such an attacking aircraft or missile was further enhanced.

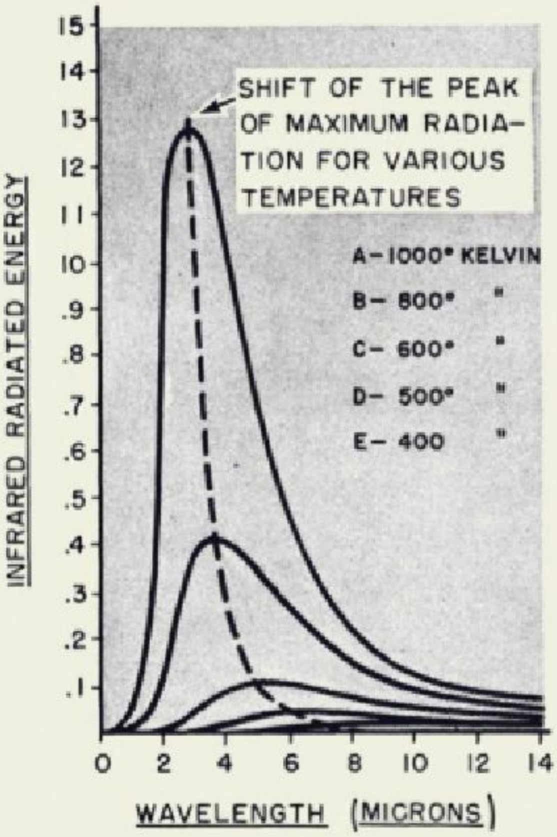
Portion of Electromagnetic Spectrum Showing Regions Used for Radar and Infrared Homing

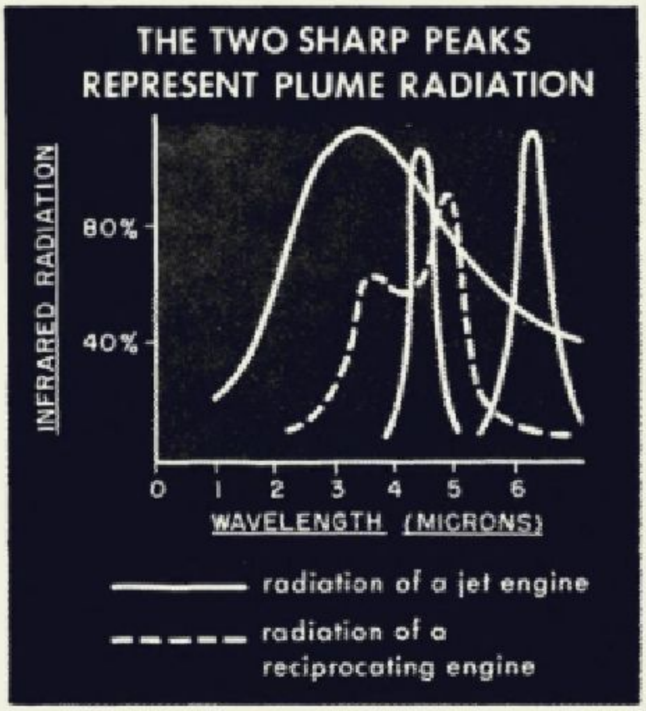


The micron, equal to 1 millionth of a meter or 1/10,000 of a centimeter, is used to express wavelength in the infrared region. We have seen how radar homing can be employed in the centimeter range of radiation. Infrared homing is generally employed in a limited range of the infrared spectrum from about 1.5 to 6 microns.

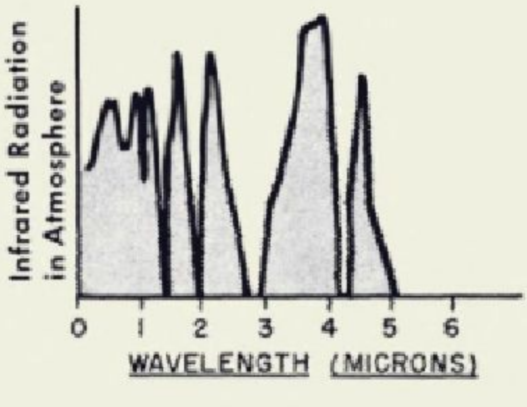
Infrared Homing Techniques (contd.)

In the region from about 0.8 to 1.5 microns most objects radiate less energy, but detectors which are capable of photographing the image are available. Below 0.8 micron we find visible light, ranging from about 0.75 to 0.4 micron from the infrared through ultraviolet. Radiation from aircraft engines, either reciprocating or jet types, appears primarily in the range of 2 to 5 microns.





INFRARED RADIATION APPLIED TO HOMING TECHNIQUES



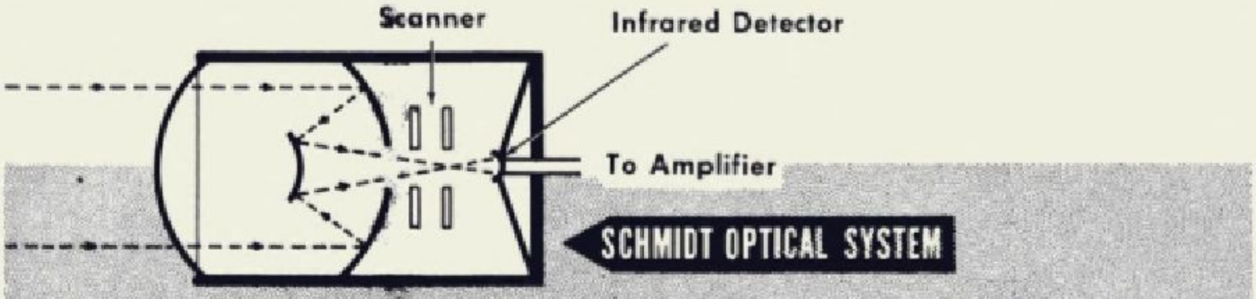
In the search for a suitable detector of radiation in the range of 3 to 5 microns, the photoconductivity of lead sulphide was found suitable in 1932. Practically all infrared devices developed in World War II utilized lead-sulphide cells. However, by 1944 lead-selenide photoconductive cells were also ready for laboratory use. Since that time lead-telluride, germanium- and indium-antimonide have been considered as detectors in this range of radiation.

Infrared Homing Techniques (contd.)

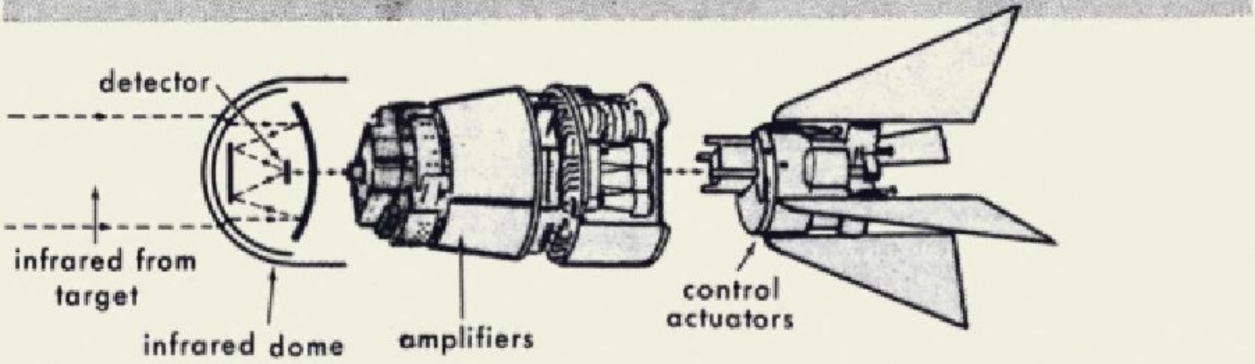
In order to increase the sensitivity of an infrared homing system the detector is placed at the output of an optical system of the *Schmidt* type. Since a-c signals can be amplified more easily than d-c, the scanner in front of the infrared detector cell is used to modulate the input signal. The parabolic mirror, which is usually about 3 inches in diameter, spins on an eccentric axis giving a reception pattern somewhat similar to a conical scan-radar. The whole optical system may be arranged to be movable about its axis so that it can rotate into the direction of the maximum heat signal. This motion is transferred by electrical means to a servosystem which can vary the control surfaces to bring the missiles into the correct course.

Infrared systems suffer from rather severe attenuation factors in the atmosphere, the optical system and the detector-response characteristics. For instance, in a typical situation only about 3% of the available heat energy at the source may be available for useful application in the system. Although the transmissivity of infrared radiation has been found to be greater than that of visible light under all weather conditions, even with fog or through clouds it is quite small under the latter conditions. Despite these limitations, the use of infrared homing equipment for certain applications, such as air-to-air missiles has been found to be quite effective.

THE ENTIRE OPTICAL SYSTEM MAY BE
ARRANGED TO BE MOVABLE ABOUT ITS AXIS

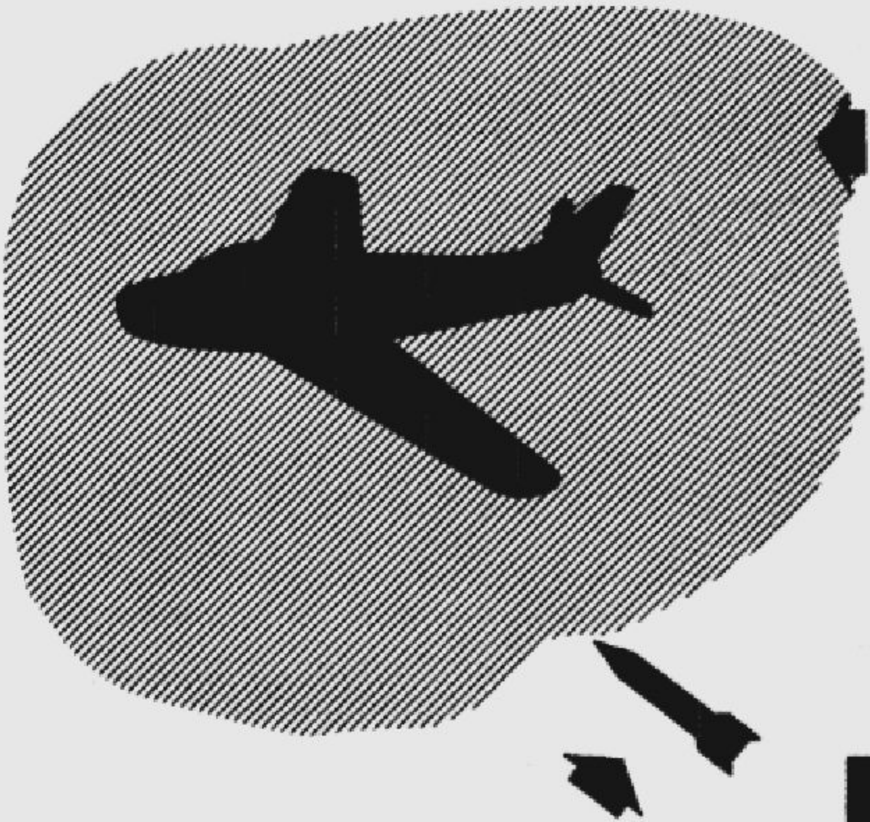


SCHMIDT OPTICAL SYSTEM



INFRARED GUIDANCE SYSTEM

Proximity Fuzing



SHADED AREA covers the region in which sufficient reflected signal is available from the target to actuate the proximity fuze.

MISSILE CARRYING PROXIMITY FUZE can receive sufficient reflected signal from the target to detonate warhead as soon as it approaches the shaded area. Thus, it DOES NOT NEED TO CONTACT THE TARGET TO DESTROY IT.

Proximity Fuzing of a Missile Can Increase the Kill Probability

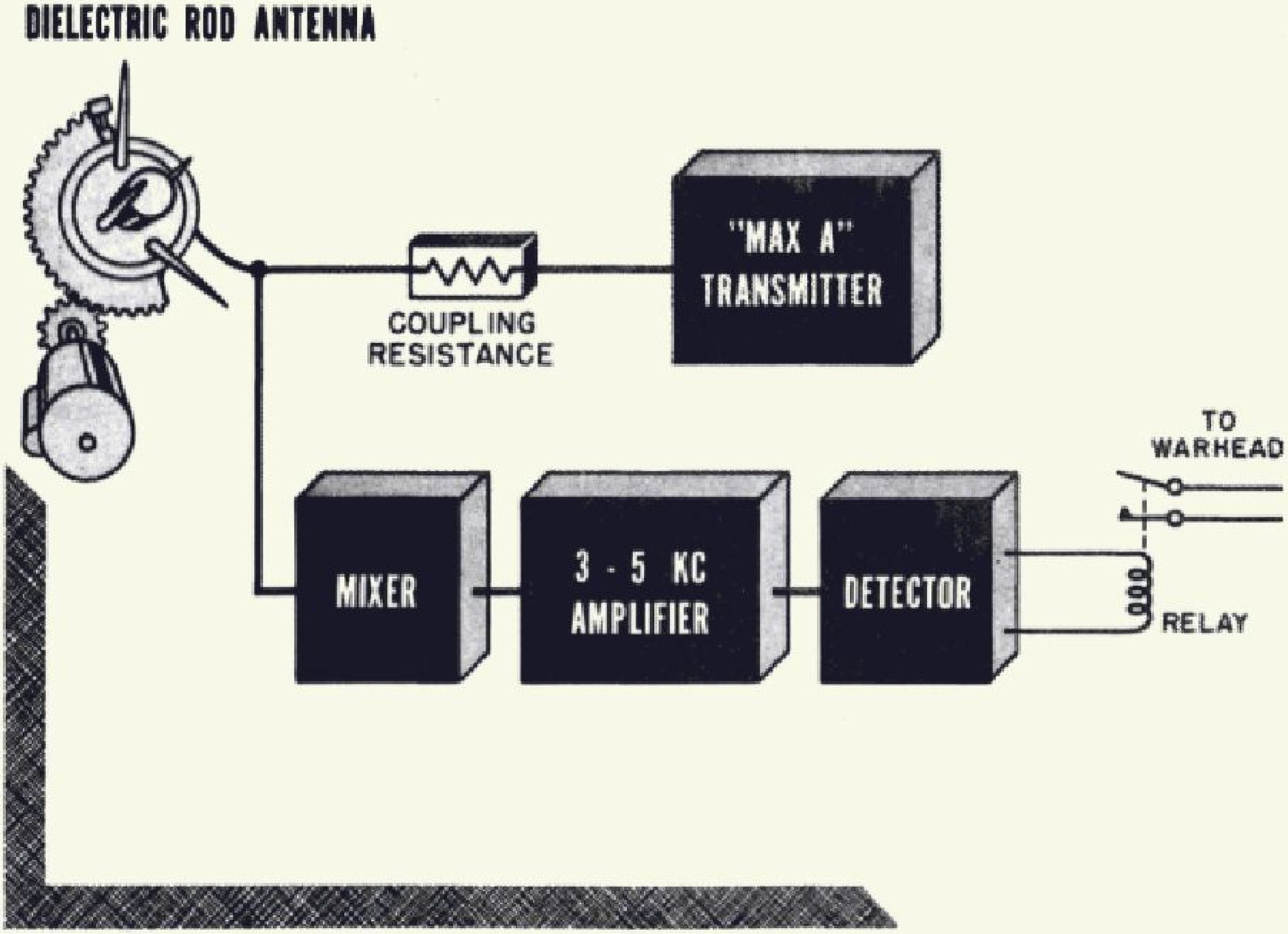
Even with accurate command or beam-guidance and a homing system it may not be feasible to obtain enough direct hits against high-speed targets to permit the utilization of contact fuzes for detonation of the warhead. Also, it is not practical to use a mechanical preset fuze. Thus, proximity fuzes are often essential to the destruction of a high percentage of the targets. A variety of proximity-fuzing arrangements were developed during World War II. From this side of the World, their application to antiaircraft shells was the major operational feat. However, the Germans did extensive development work on a number of systems which they had hoped to use in both defensive and offensive missiles.

Most of the U.S.A. antiaircraft shell fuzes operated on the basis of a Doppler-frequency shift between a radiated and reflected signal. The same oscillator, which provided the transmitted signal, also served as a beat-frequency source for converting the reflected signal to an a-f signal. This signal was amplified further to fire a small thyratron tube controlling the squib in the warhead.

Proximity Fuzing (contd.)

A typical German missile fuze development was conducted in conjunction with the *Max A* homing equipment described earlier. In this arrangement some of the voltage from the 7700 mc oscillator was fed through a coupling resistance to the input of a relatively simple receiving channel, which also picked up reflected signals from the target. The local oscillator signal of 7700 mc beat with the reflected signal to give an audio output ranging from 2 kc to 5 kc, which was selectively amplified. The detected output was used to operate a relay, which controlled the firing of the warhead.

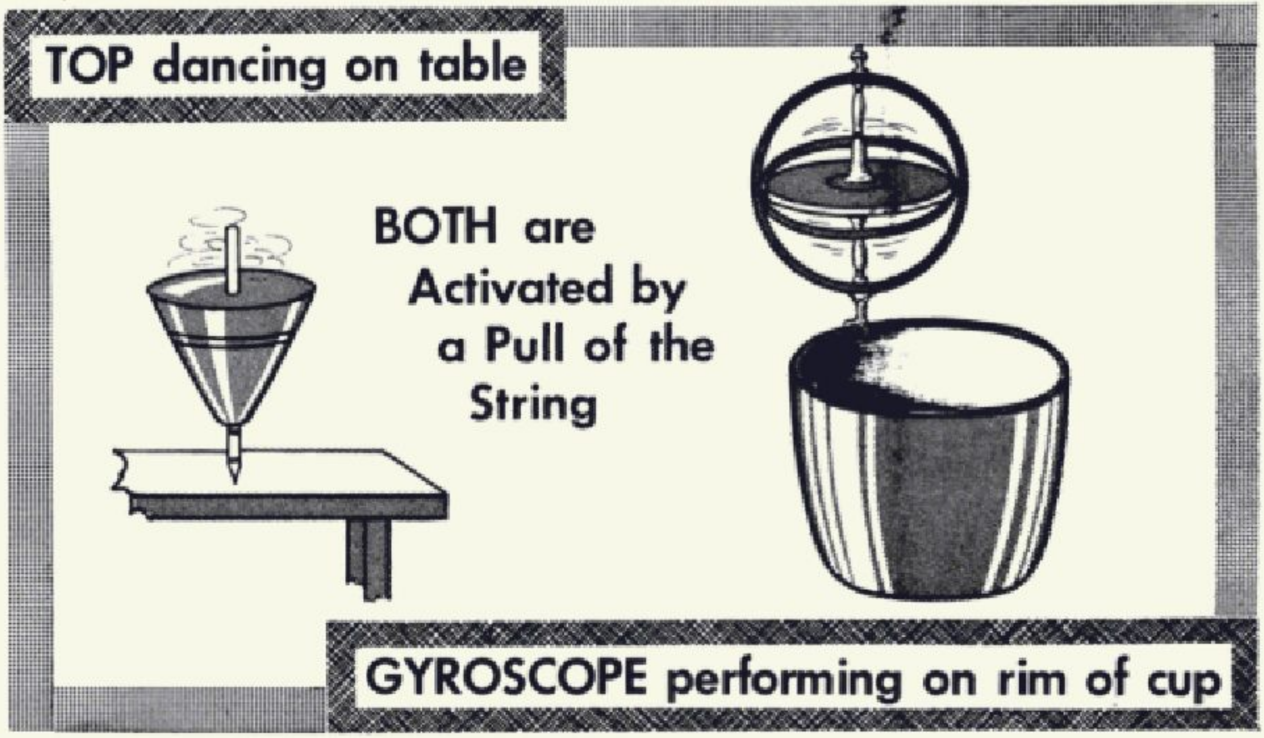
A TYPICAL GERMAN MISSILE FUZE DEVELOPMENT



Several other types of fuzes, utilizing Doppler effects, frequency modulation, antenna-interference variations, electrostatic fields, magnetic-field effects, acoustical and optical qualities of the target were in various stages of development at the end of World War II. An analysis of all of these types by one of the German developers indicated that the most promise probably lies at the very highest radio-frequencies and at the longer wavelengths of infrared radiation.

Introduction to Gyroscopes

Ordinary tops and small toy gyroscopes are generally driven by one pull of a string to bring their mass up to a velocity which keeps them in stable motion for a short time. These commonplace examples utilize the same fundamental principles as those of the much more elaborate and precise gyroscopes so essential to present-day navigation. The top is a good example of simple gyroscopic action. However, it is not suspended in any sort of frame. The toy gyroscope, available in almost every part of the world, is suspended in a frame, and is an example of a single-axis type.


TOP dancing on table
BOTH are Activated by a Pull of the String
GYROSCOPE performing on rim of cup

Ever since the invention of the wheel, man has witnessed gyroscopic action to some degree in this familiar form. The invention of the top is credited to the Chinese many centuries ago. Leon Foucault, a French scientist, is acknowledged as the inventor of the gyroscope — as we know it — in 1852. However, 20 years earlier a German, Herr Bohnenburger, made similar experiments. At that time a Scot, Edward Sarg, suggested an experiment similar to that performed by Foucault.

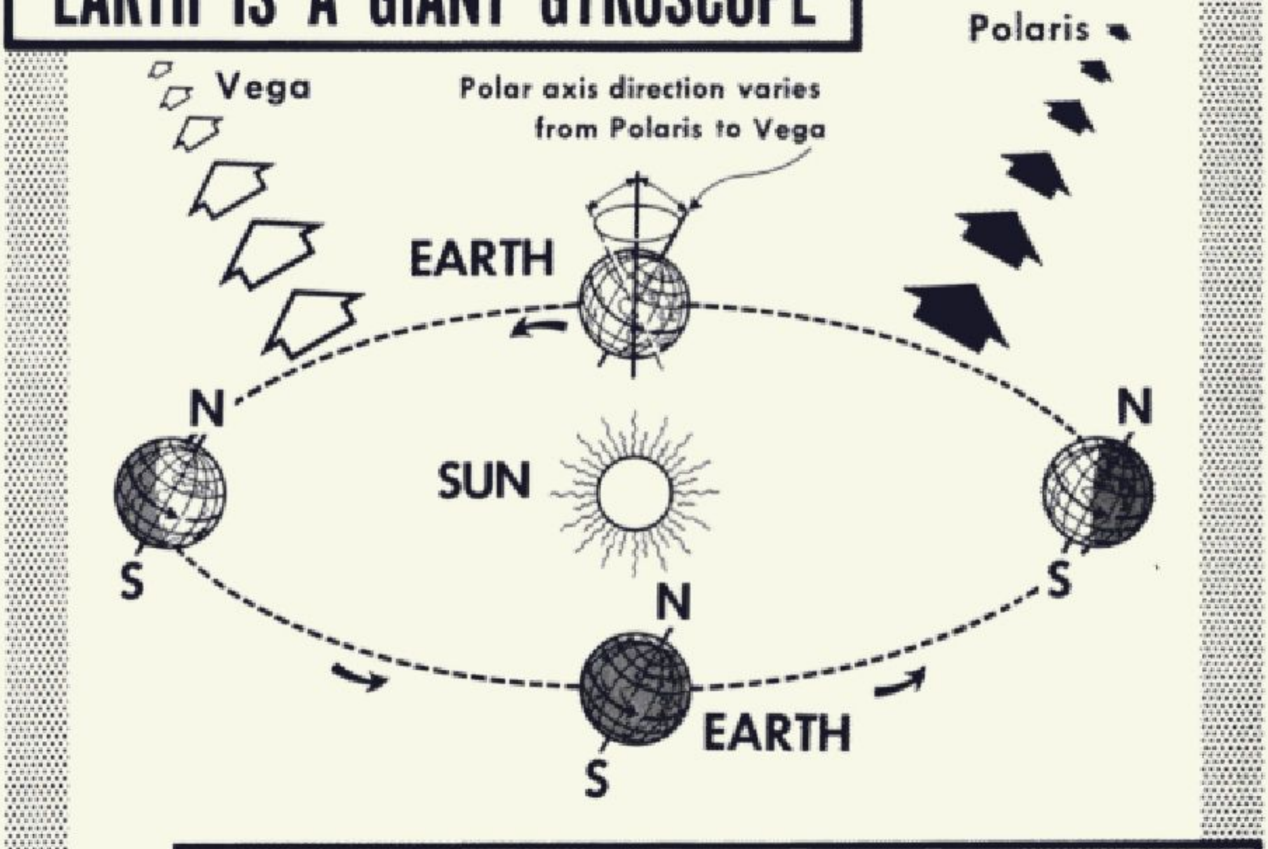
In his experiment Foucault utilized the fact that the gyro axis points at a fixed direction in space. In accordance with one of Newton's laws of motion the spinning rotor resists changes in its direction of motion. In Foucault's experiment a scale mounted around and separate from the gyro frame followed the rotation of the Earth, while the gyro axis pointed at a fixed direction in space thus indicating the Earth's relative motion. The gyroscope even received its name from this application (*gyro* for revolution and *scope* for observer; thus, it is literally a revolution observer).

The Planet Earth as a Gyroscope

Actually, gyroscopic action is as old as the universe. Ever since matter started rotating about a point in space gyroscopic principles were in action. In fact, we spend most of our lives on a gyroscope, the Earth. Within the knowledge of man its axis has pointed toward the North Star (Polaris) generally. As we all know, it rotates at 1 revolution per 24 hours, and travels around the Sun in an elliptical orbit at 1 revolution per year. However, due to its mass it develops the substantial angular momentum of 6.5×10^{31} tons ft^2 per sec.

The fact that the tilted poles of the Earth are pointed in a relatively fixed direction due to its gyroscopic behavior accounts for the four seasons as it rotates about the Sun at more than 60,000 miles per hour. Even than a 47° deviation of the Earth's axis takes place every 12,900 years due to an effect known as precession and causes the seasons to vary somewhat over this rather long period.

EARTH IS A GIANT GYROSCOPE

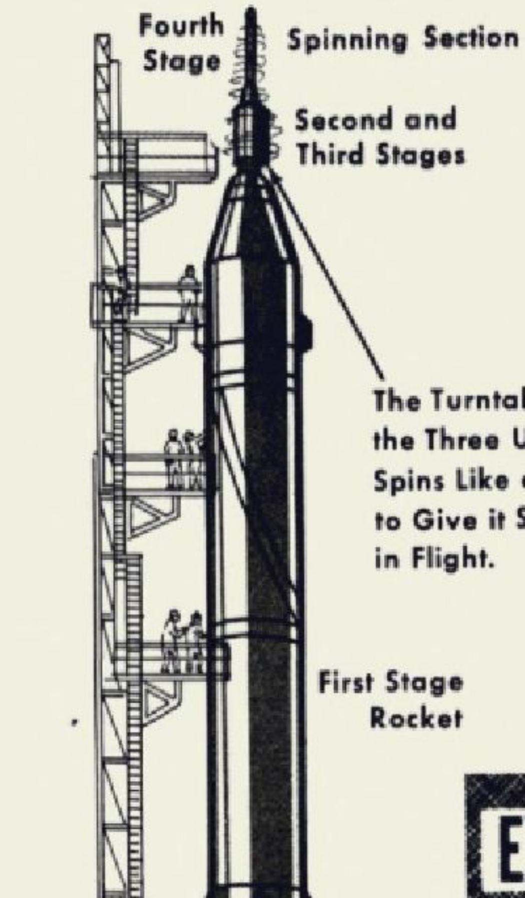


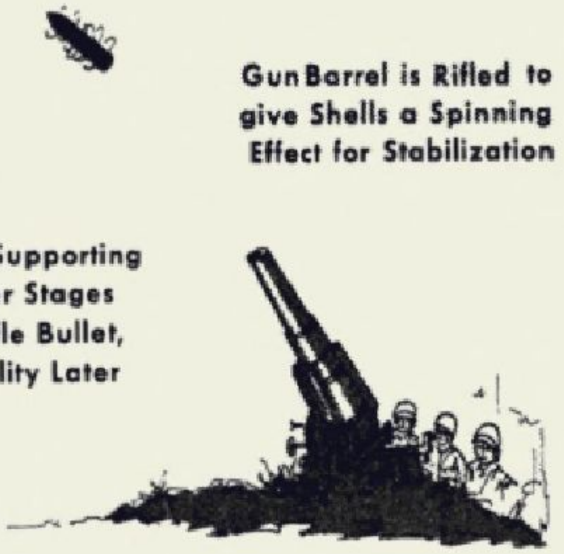
It rotates one revolution per day on its axis and travels around the Sun in an elliptical orbit one revolution per year. The polar axis tilts due to gyroscope precession of the spinning Earth

Other Gyroscopic Examples

Other rather common gyroscopic examples are found in all types of spinning and rotating bodies. For instance, gun barrels are rifled to give shells a spinning effect for stabilization. Simple rockets are arranged with jets exhausting in the proper direction to rotate them for the sake of stability in their trajectories. Of course, spinning objects in the air can produce other than the perfectly directed courses attainable in a vacuum. Spinning objects revolving against an air cushion will tend to curve rather than follow a straight line. However, if allowances are made for this effect, the spinning or rotating action will still provide stability in a trajectory.

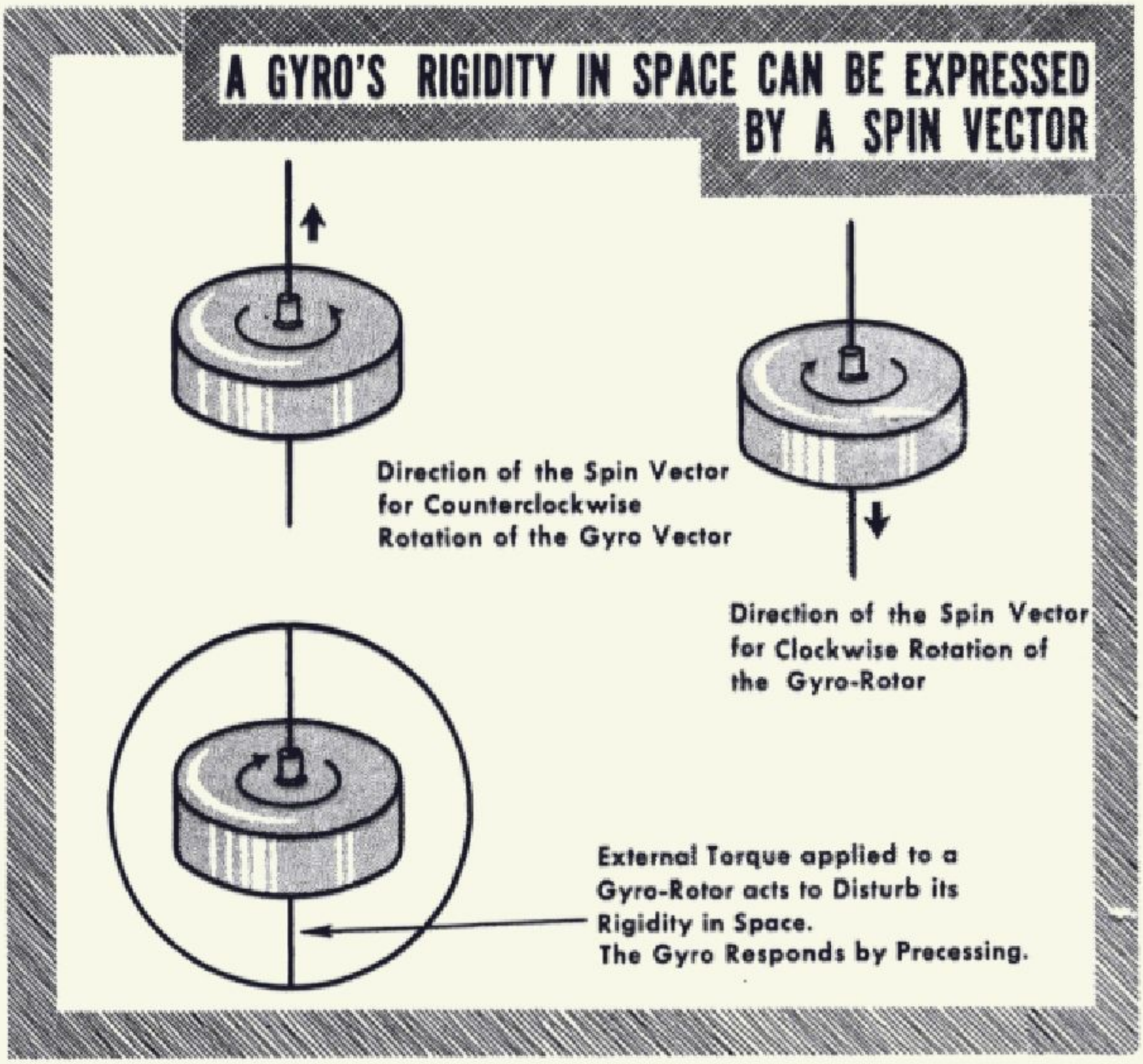
Gyroscopic stabilization may be realized by spinning the object to be controlled; also, by utilizing a gyro rotor of such large mass that it dominates the stability aspect when rotated at the required velocity; or by incorporating one or more small gyroscopes inside of the object and utilizing information derived from it to keep the object on a desired course. One of the most recent applications of rotating a rapidly moving mass to give it stability is found in the spinning of satellites.


Fourth Stage
Spinning Section
Second and Third Stages
The Turntable Supporting the Three Upper Stages Spins Like a Rifle Bullet, to Give it Stability Later in Flight.
First Stage Rocket


Gun Barrel is Rifled to give Shells a Spinning Effect for Stabilization

EXAMPLES OF GYROSCOPIC ACTION

Rigidity in Space



A GYRO'S RIGIDITY IN SPACE CAN BE EXPRESSED BY A SPIN VECTOR

Direction of the Spin Vector for Counterclockwise Rotation of the Gyro Vector

Direction of the Spin Vector for Clockwise Rotation of the Gyro-Rotor

External Torque applied to a Gyro-Rotor acts to Disturb its Rigidity in Space. The Gyro Responds by Processing.

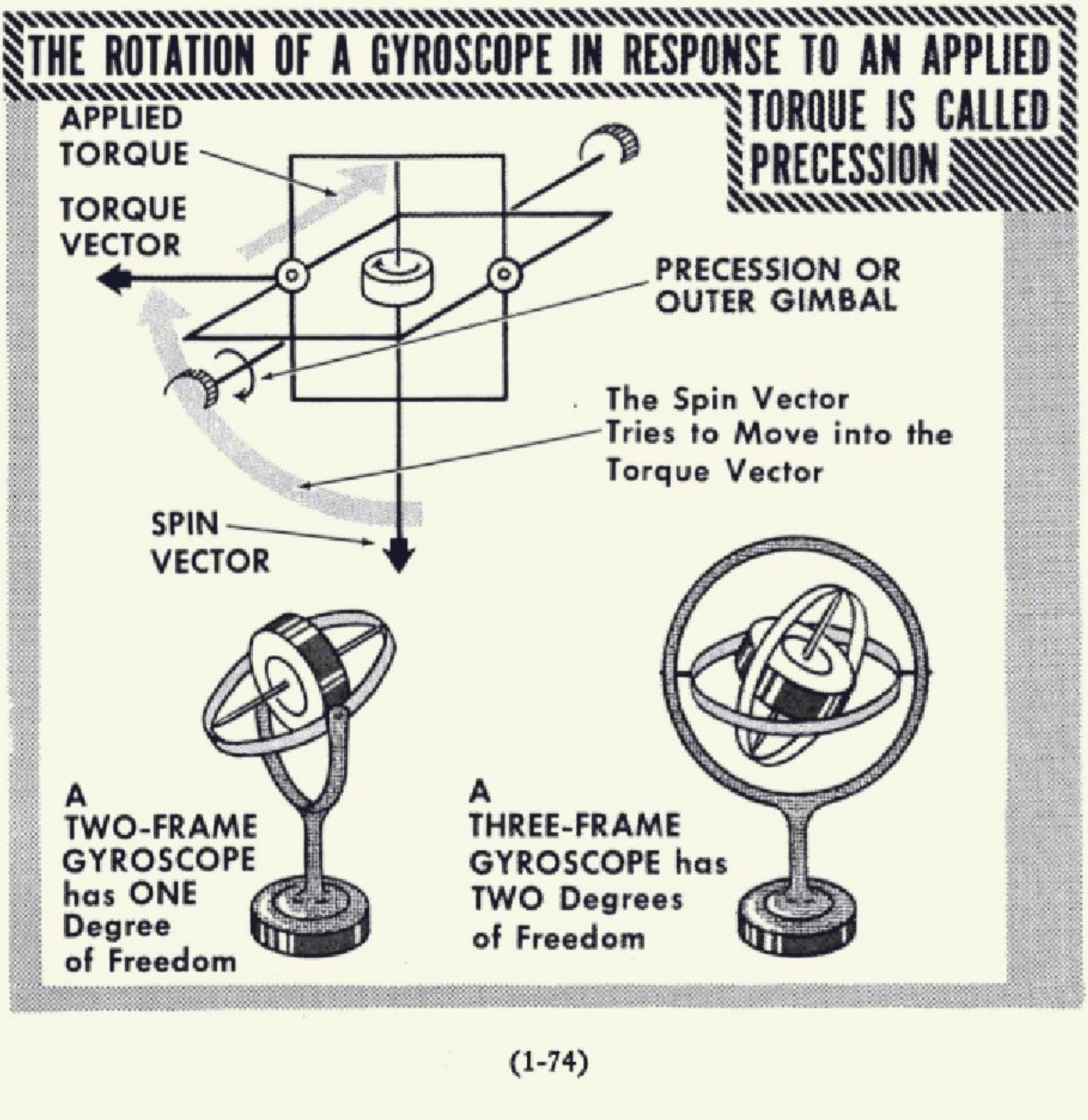
One of the principal characteristics of a gyroscope — axial rigidity in space — has already been mentioned several times previously. This feature is its prime quality as a device for navigational purposes. Its fixed direction can be utilized for maintaining a desired heading, provided it can be associated with adequate references so that the rigidity of the rotor axis to external torques is meaningful to the navigator.

The gyroscopes previously mentioned have either been without a supporting ring about their rotational axis — as in the case of the top and the Earth — or with a single ring as in the case of the simple toy gyroscope. Also, one could mention the simple compass of the type used by Foucault in his experiment. However, navigational gyros are suspended in two or three rings or gimbals — as they are called — giving them an ability to respond to forces about the axes with which they are associated.

Precession

When a gyroscope responds to deviating forces about its axes, it displays another very important characteristic known as *precession.* Spinning tops wobble about their axes. Especially when they slow down, they allow external forces to produce more effect than when they are spinning fast. Also, the Earth slowly describes a significant axial deviation in space over a long period of time. However, to make precession useful for navigational purposes, it is necessary in a man-made gyroscope to provide one or two frames or gimbals in addition to the frame surrounding the spin axis.

In these frames the gyro realizes one or two degrees of freedom in which precession can take place. The effect of precession is simply such that when a force is applied at right angles to the axis of the rotating mass, the gimbal ring supporting the axis of the rotating mass will not move in the direction of the applied force but will rotate at right angles to it.



THE ROTATION OF A GYROSCOPE IN RESPONSE TO AN APPLIED TORQUE IS CALLED PRECESSION

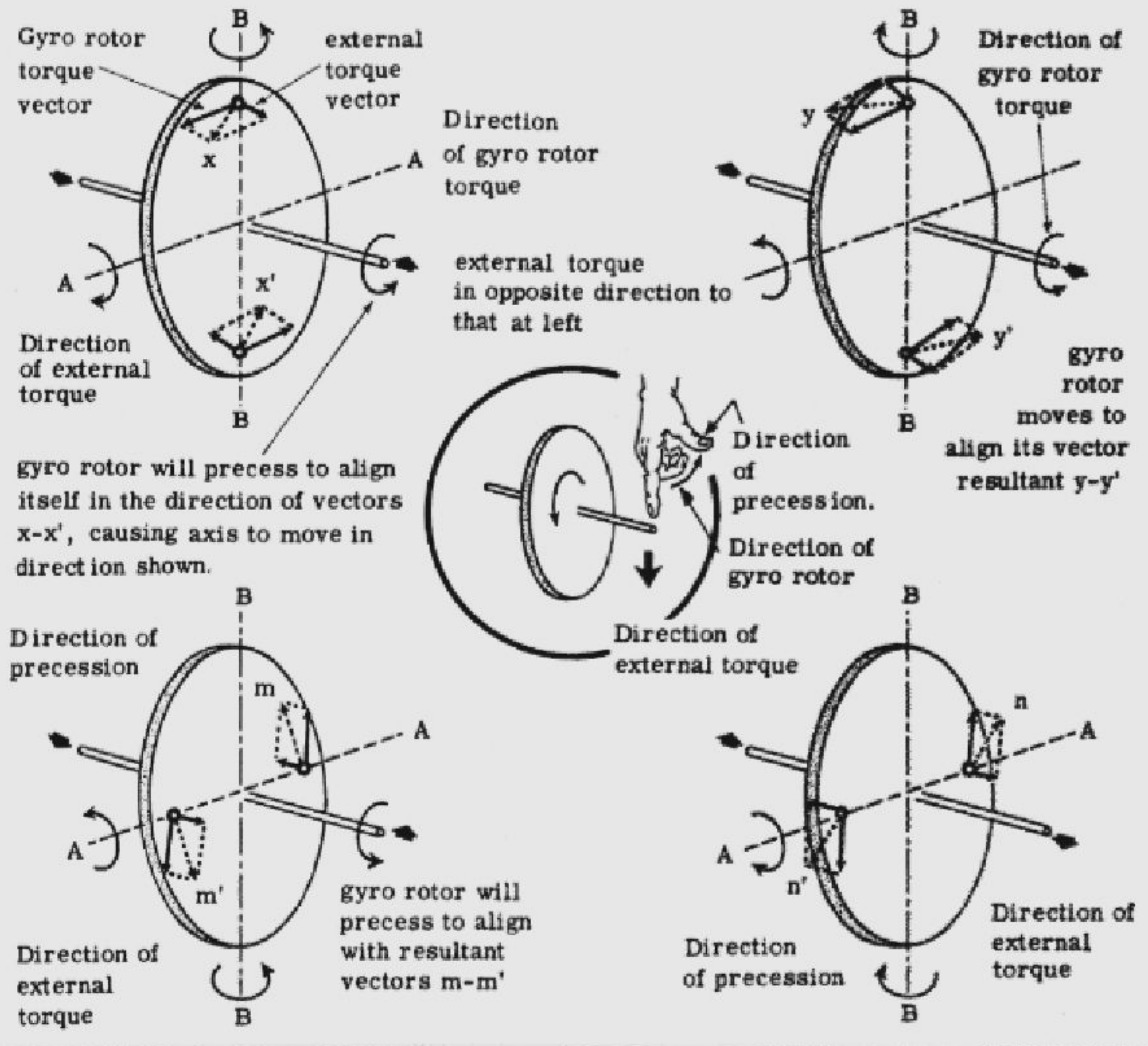
APPLIED TORQUE
TORQUE VECTOR
PRECESSION OR OUTER GIMBAL
The Spin Vector Tries to Move into the Torque Vector
SPIN VECTOR
A TWO-FRAME GYROSCOPE has ONE Degree of Freedom
A THREE-FRAME GYROSCOPE has TWO Degrees of Freedom

Precession (contd.)

The precession of a rotating gyro wheel, when subjected to external torques can be readily explained through the use of vector diagrams. By considering the torques as being applied to small unit masses in a gyro rotor wheel, it is rather easily understood that the rotor shifts to align itself with the direction of the vector sum of its torque and that of the external torque.

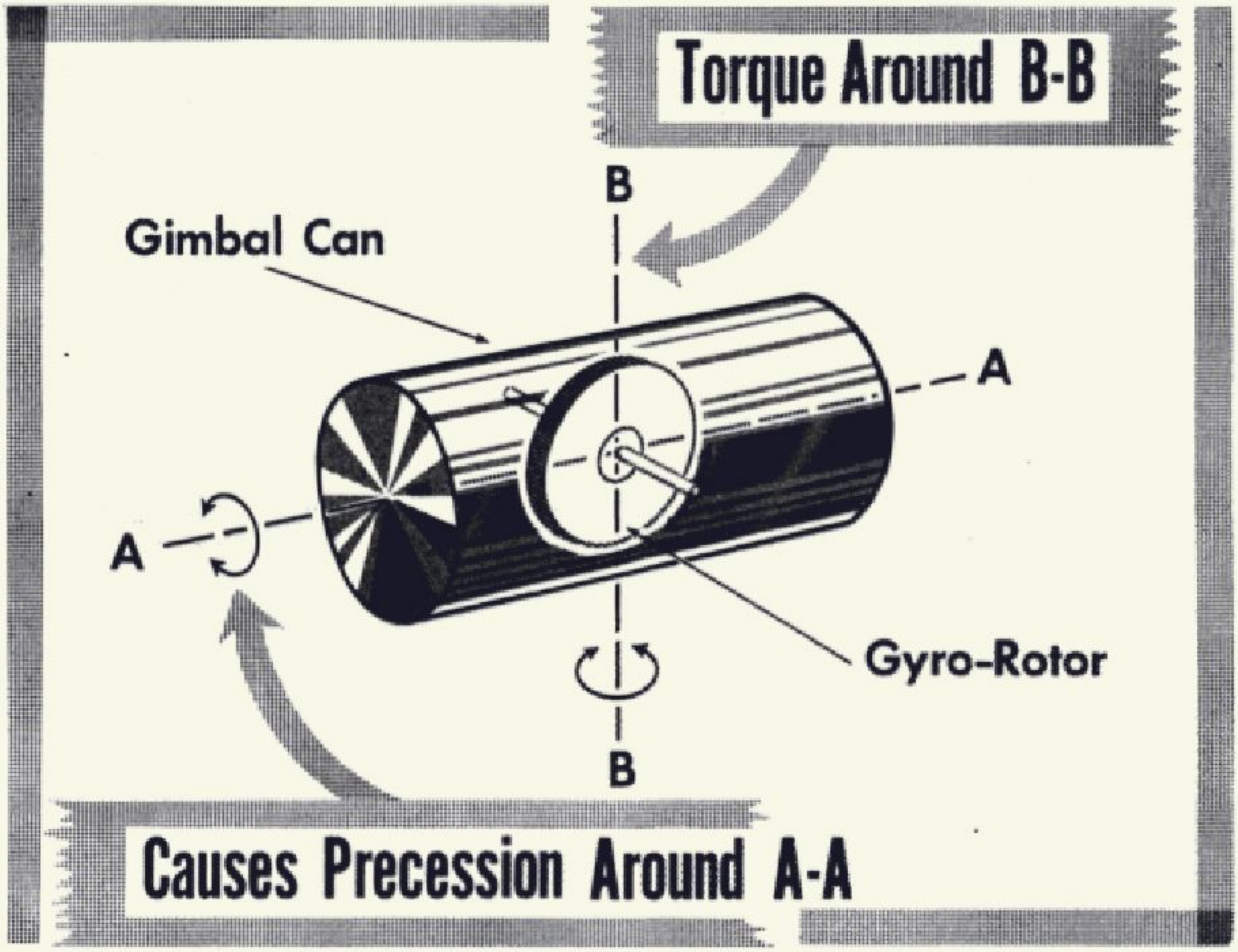
A simple rule which may be applied to determine the direction of precession is that of pointing the forefinger of the right hand in the direction of the external torque as seen from the rotor axis, closing the other fingers in the direction of the rotation of the gyro rotor, and noting the direction in which the thumb points.

EXTERNAL TORQUE APPLIED AROUND AXIS A-A


Gyro rotor torque vector
external torque vector
B
x
A
x'
A
Direction of external torque
B
Direction of gyro rotor torque
external torque in opposite direction to that at left
B
Direction of gyro rotor torque
y
y'
gyro rotor moves to align its vector resultant y-y'
B
gyro rotor will precess to align itself in the direction of vectors x-x', causing axis to move in direction shown.
Direction of precession.
Direction of gyro rotor
Direction of external torque
B
Direction of precession
m
A
A
m'
gyro rotor will precess to align with resultant vectors m-m'
Direction of external torque
B
B
n
A
A
n'
Direction of precession
Direction of external torque
B

EXTERNAL TORQUE APPLIED AROUND AXIS B-B

Precession (contd.)



From the diagrams on page 1-75, it is apparent that when a gyro rotor is sealed inside a gimbal can, variations in external torque around axis B-B will cause the gimbal-rotor assembly to precess about axis A-A. As shown on page 1-81, signals generated by the precession output are used to bring the gyro back to its original direction in space. The rate at which the gyro-rotor moves toward the new torque vector in precession is directly proportional to the applied torque, but indirectly proportional to the angular momentum of the gyro wheel about its own axis.

The basic relationship describing gyro-rotor behavior is expressed by the formula $\overline{W}_p = \overline{T}/\overline{H}$. $\overline{W}_p$ is the absolute precessional velocity of the spin axis (radians/second), $\overline{T}$ the applied torque (dyne-centimeters), and $\overline{H}$ the rotor angular momentum (gram-centimeters^2 per sec).

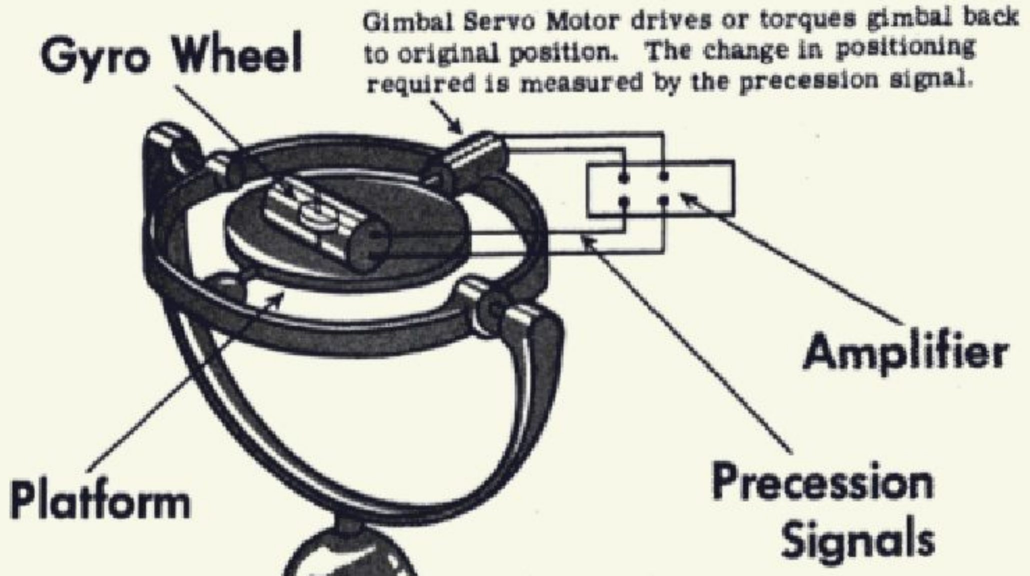
Since the gyro's precessional quality is largely dependent on $\overline{H}$, they are generally rated in terms of the rotor angular momentum. Gyroscopes are often referred to as 10^3, 10^5, or 10^6 units. These numerical quantities are a measure of $\overline{H}$, which is variously expressed as gram-centimeters^2 per second, dyne-centimeters-seconds per radian, or dyne-centimeters per radian per second — all of which are equivalent.

How the Gyroscope is Employed

The output of the gyro is proportional to the torques to which it may be subjected in its operational application. If it has only one gimbal around which precession can be measured, it can respond only to torques in one direction, and is said to have *one degree of freedom*. One can study the manner in which precession signals from a single gimbal gyro may be utilized by considering that the gimbal can is mounted on a movable platform rather than an aircraft or missile frame.

With the application of external torque about the platform axis both it and the attached gyro will start to move to a new position depending upon the amount and direction of the torque. Simultaneously a signal will be generated due to the gyro precession. This voltage can be picked off and fed through an amplifier. Then it is fed back through a motor which restores the platform and the attached gyro to their original positions. The platform to which the gyro container is attached may be the body of an aircraft or missile which would be restored to its original position by gyro-stabilization. Since the single-degree-of-freedom gyro can precess in only one plane of motion, an additional gyro is required for each additional control axis.

HOW PRECESSION IS EMPLOYED

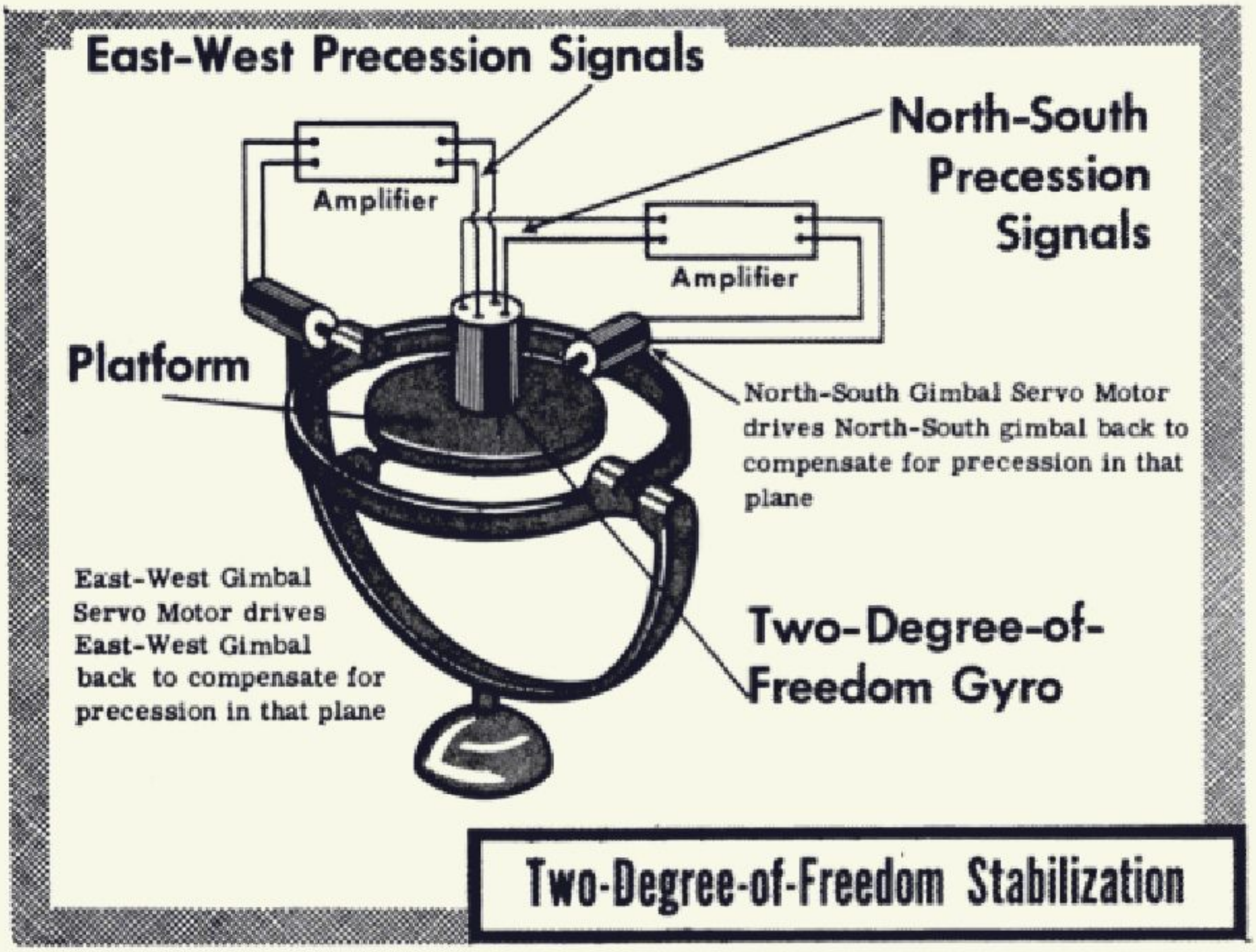

Gyro Wheel
Gimbal Servo Motor drives or torques gimbal back to original position. The change in positioning required is measured by the precession signal.
Amplifier
Platform
Precession Signals

Single-Degree-of-Freedom Stabilization

How the Gyroscope is Employed (contd.)

If a gyro has two gimbals around which precessions can be measured, it can respond to torques in two directions, and is said to have *two degrees of freedom.* For this type of unit two separate signals can be made available, and can be applied to two platform gimbals to restore them to their positions when fed through suitable servo-loops. Thus, it is possible to obtain signals from one gyro unit to correct for any two of three possible deviations — roll, pitch and yaw.

A single-degree-of-freedom gyro will provide for correcting control in only one of these frames. Both types of gyros have been employed in a variety of applications. Some prefer the single-degree-of-freedom type because it is simpler to build and hold to tolerances in manufacturing, while others prefer the two-degree type because two units instead of three will suffice to control a system in three planes of motion.


East-West Precession Signals
North-South Precession Signals
Amplifier
Amplifier
Platform
Two-Degree-of-Freedom Gyro

North-South Gimbal Servo Motor drives North-South gimbal back to compensate for precession in that plane

East-West Gimbal Servo Motor drives East-West Gimbal back to compensate for precession in that plane

Two-Degree-of-Freedom Stabilization

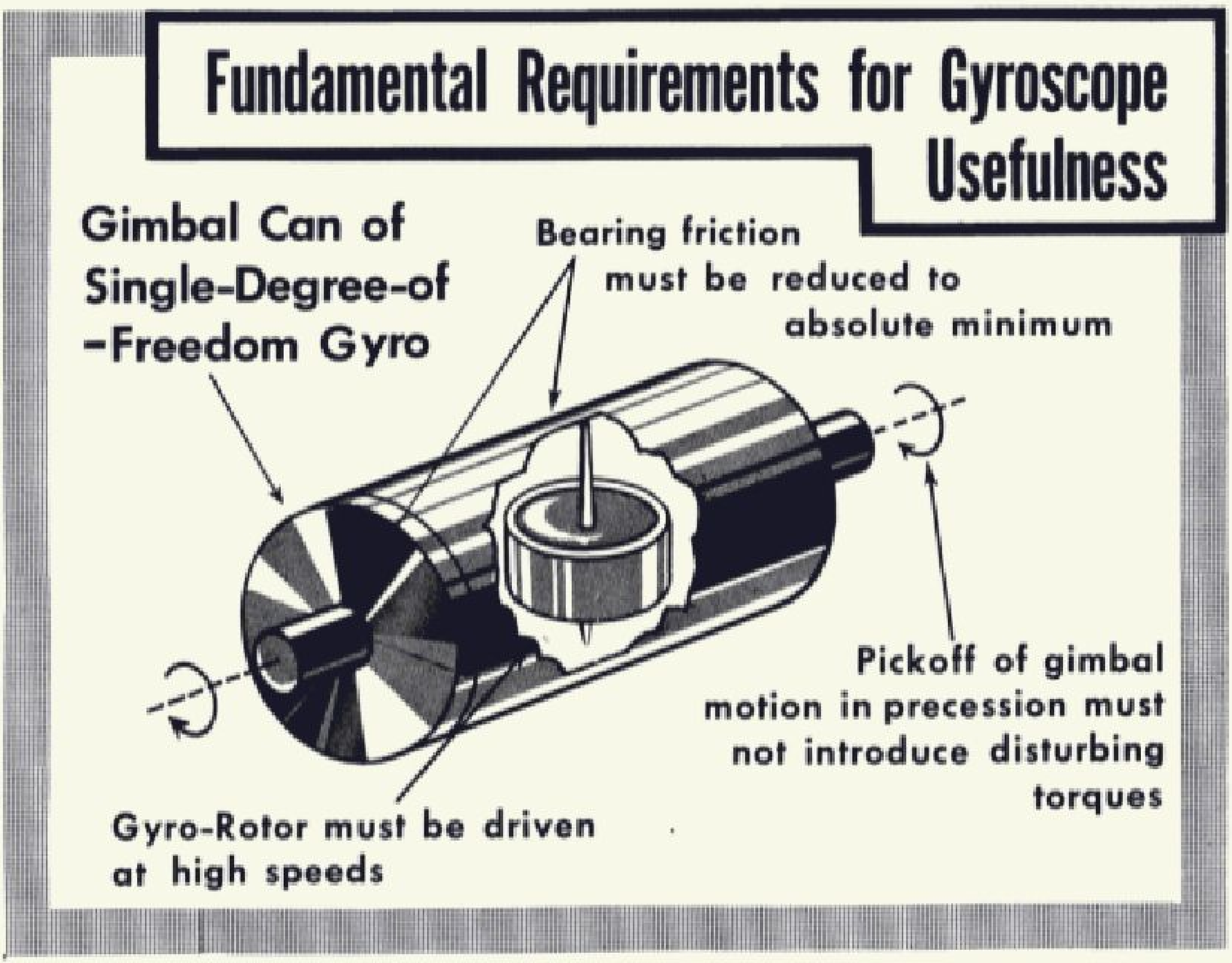
If we replaced the platform with a missile body, the principles would be the same as shown. However, several other elements would become necessary to provide control or guidance to the appropriate thrust or surface component. These might include valves, actuators, and a feedback loop.

The Navigational Possibilities of the Gyroscope

Although the gyroscope offered features which appeared to link it closely with navigational possibilities as related to motion about the surface of the Earth, it was not until the beginning of the twentieth century that any major applications were made. Three factors influenced this situation:

1. The need for a suitable means for spinning the rotor at high velocities. It is not uncommon in present-day gyroscopes to find rotor speeds in excess of 20,000 rpm.
2. The development of low-friction bearings or other means of supporting the rotor at these speeds as well as providing the lowest possible friction at the gimbal mounts.
3. The development of suitable arrangements for utilizing the gimbal motions for control purposes. Any appreciable restraining forces on the gimbal movements will introduce errors.

These three factors continue to dictate the direction of gyroscope development despite the many applications which have been realized to date. The continuing demand for smaller gyros with better performance characteristics keeps all of these problems alive as the designer proceeds from one application to another.



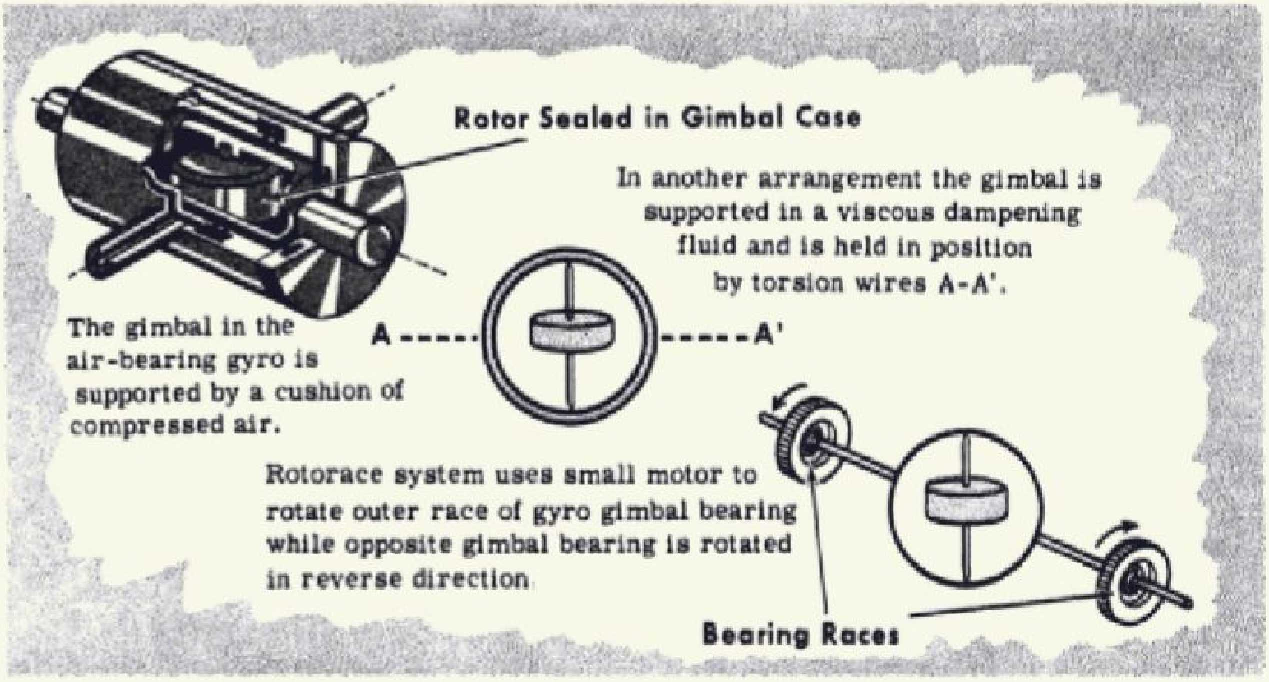
Fundamental Requirements for Gyroscope Usefulness

Bearing friction must be reduced to absolute minimum

Pickoff of gimbal motion in precession must not introduce disturbing torques

Gyro-Rotor must be driven at high speeds

Gyro Drift



In another arrangement the gimbal is supported in a viscous dampening fluid and is held in position by torsion wires A-A'.

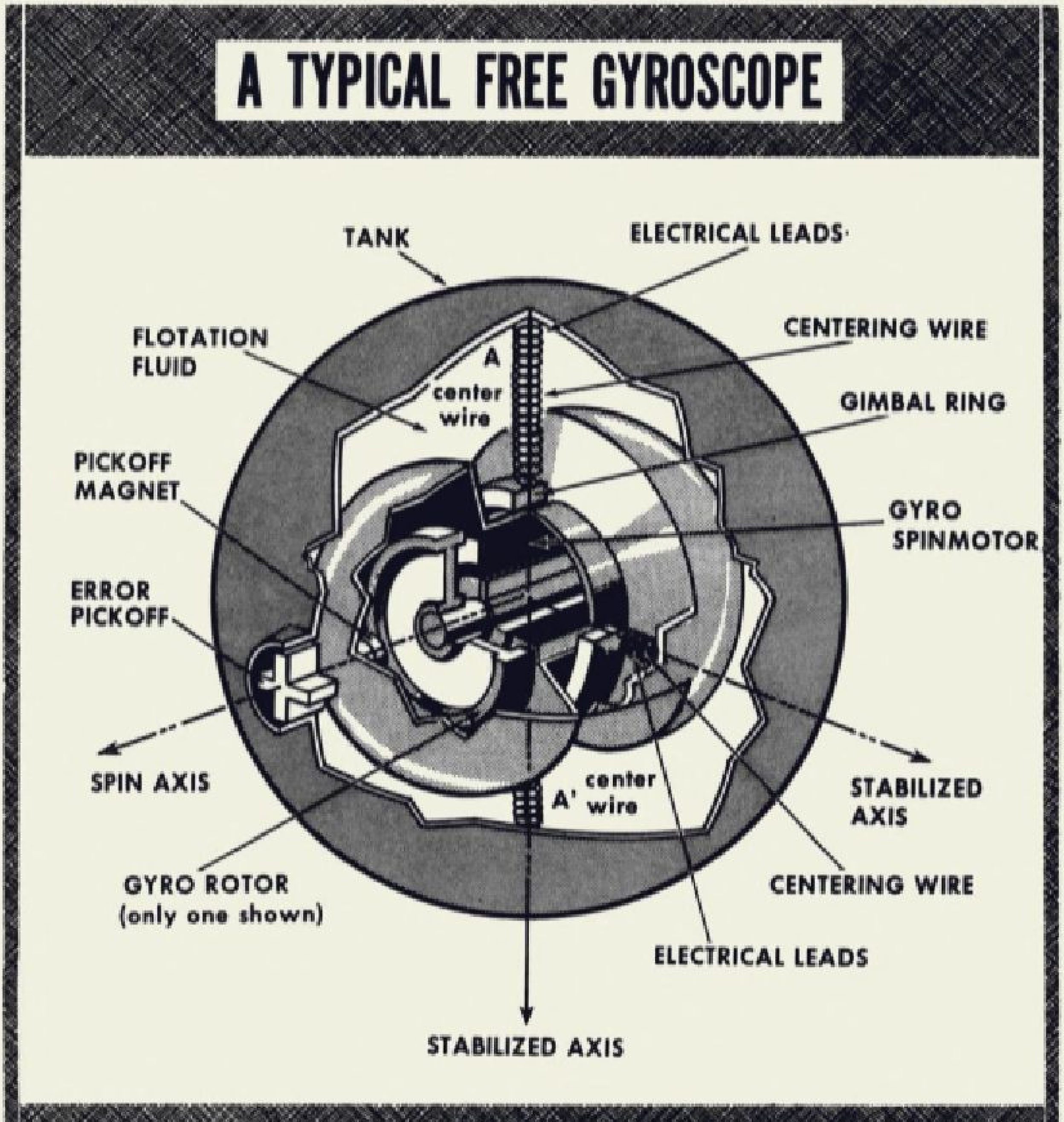
The gimbal in the air-bearing gyro is supported by a cushion of compressed air.

Rotorace system uses small motor to rotate outer race of gyro gimbal bearing while opposite gimbal bearing is rotated in reverse direction

Although a perfect gyroscope would maintain true axial rigidity in space, it is apparent from the second and third factors mentioned above that perfection can only be approached but not realized as long as there is any friction in the rotor bearings or any unbalance from gimbal restraining forces. Hence, the continual quest for better performance in these areas. The degree to which the gyro axis deviates from true rigidity is called *drift*. If a gyro is to be used for aircraft stabilization over only a short period of time, a drift of 1° per hour might be quite acceptable, but if it is to be used as a basis for accurate navigation over a longer period of time or for greater accuracy, the drift must be reduced below .1° per hour. It is apparent that a gyro of a given drift-rate will perform best over a given range if the vehicle is moving at the maximum possible speed so that it will be in operation for the shortest possible time; better still, the problem is simplified if the gyro must be depended upon only during a relatively small part of the trip.

A variety of approaches are used to reduce bearing-friction and unbalance effects. Among these are air bearings where a cushion of air is used to support the parts away from metallic contact. The gyro rotor is also in some instances sealed in a gas-filled compartment to assure uniformity of environmental conditions. The gimbals may also be floated in a fluid and only supported by centering wires or rods. It is quite apparent that a high order of mechanical precision in parts fabrication is necessary to minimize drift effects due to unbalance in the parts related to the rotor and gimbal structures. Continual progress in gyro design and production engineering promise to produce the very low drift rates essential to long-range self-contained navigation.

The Free Gyroscope



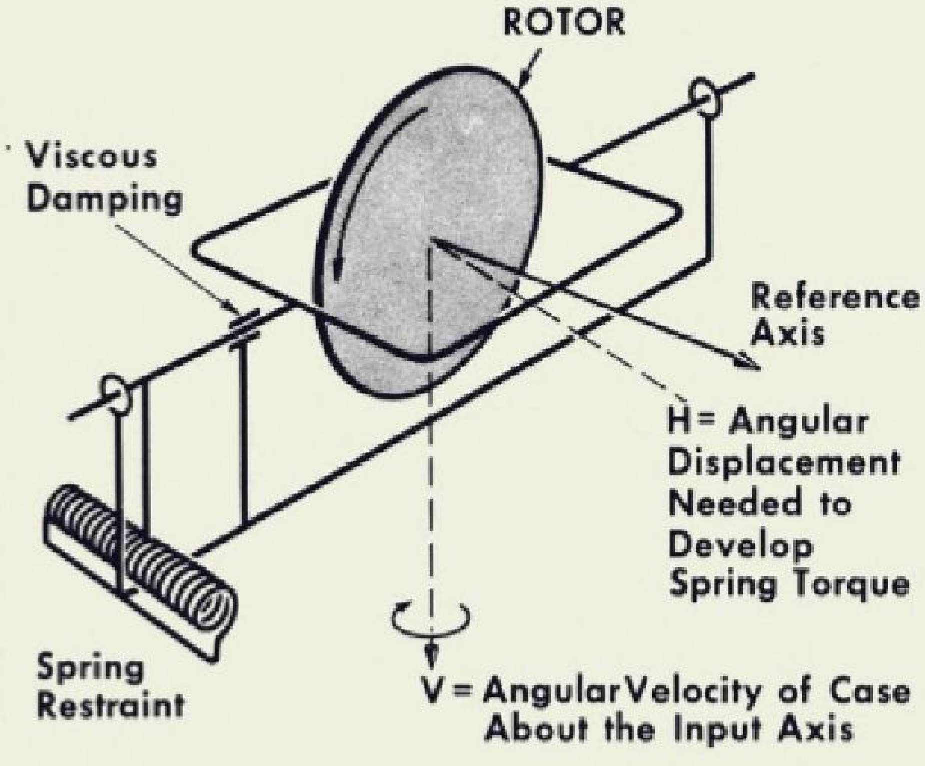
A free gyro differs from a directional or vertical gyro primarily in the fact that its axis may be oriented in any direction relative to the surface of the Earth. The rotor is caged or held in the desired direction, then uncaged or released to give the necessary gyro-action for stabilization. A typical application is for roll-stabilization. However, the free gyroscope finds a wide range of applications. For instance, the two-degree-of-freedom gyros used for missile-stabilization in a typical stable platform are free gyros.

The Rate Gyroscope

Although directional, vertical, and free gyros can sense the information necessary to determine a position in space, it is particularly important, in stabilizing any vehicle, to know the rate at which deviations and/or corrections are being applied as in the case of the autopilot. This parameter may be determined by utilizing rate gyros, which can be made by applying a restraining spring to the moving gimbal of a single-degree-of-freedom gyro. When the torque developed by turning forces is applied to the gyro, it will precess. However, the restraining springs will allow the gimbal to move only through a small arc proportional to the angular rate along the input axis.

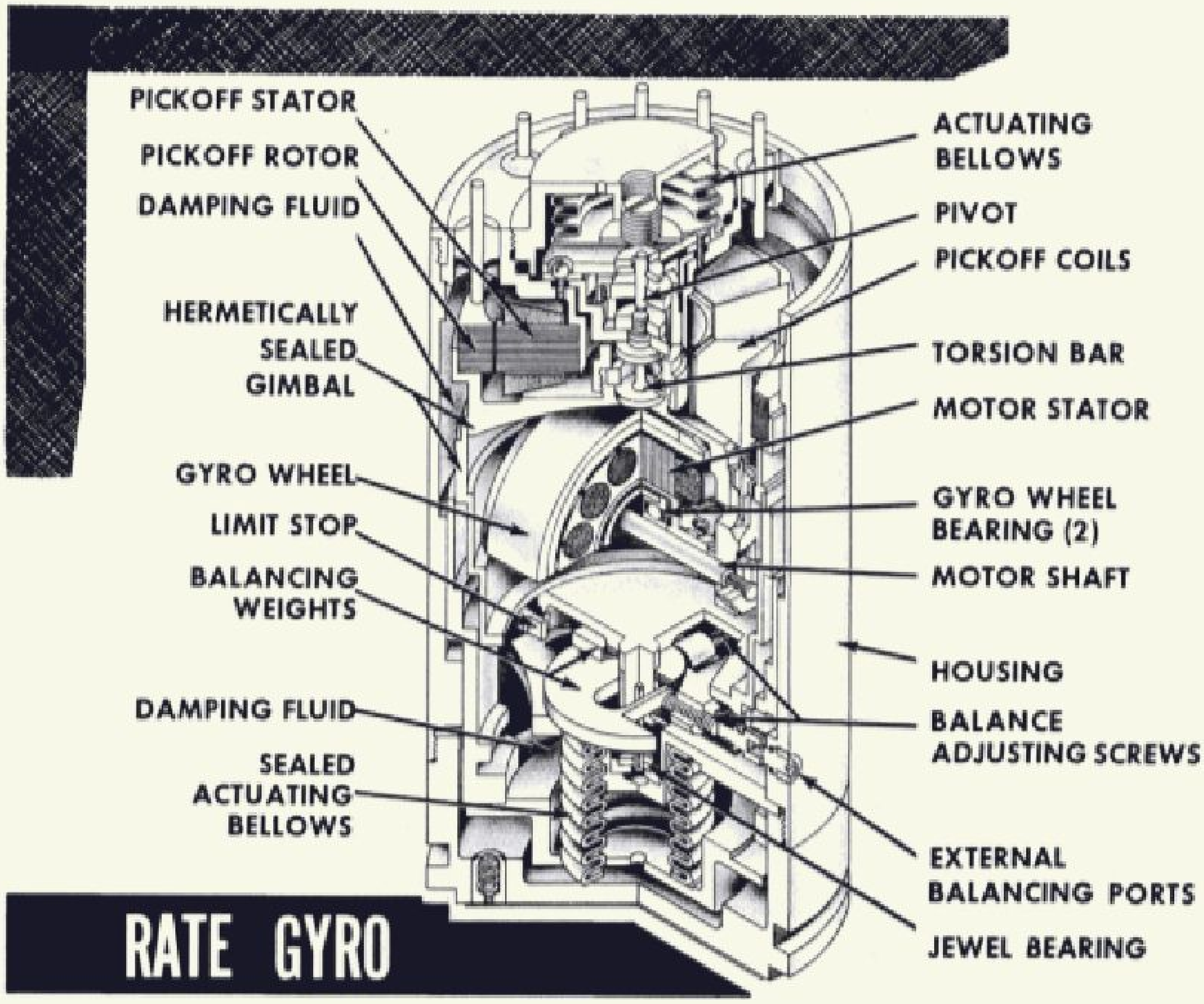
Two types of rate gyros are in extensive use. One type provides a voltage output proportional to the input rate and the gimbal displacement. The other type acts as a switch which closes a circuit when the rate reaches a predetermined value. Both units may be mounted in any position which correctly orients the input axis.

THE RATE GYROSCOPE

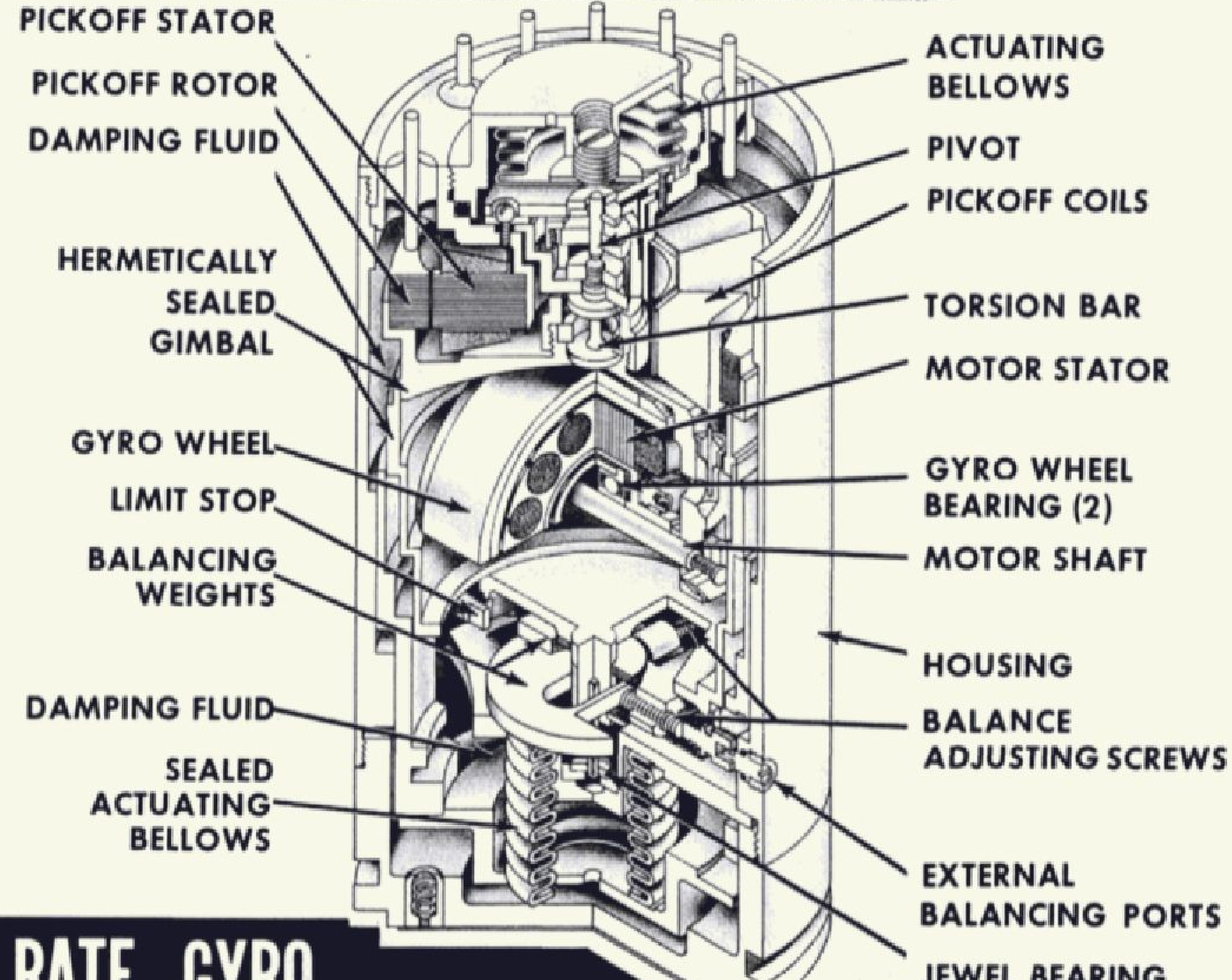

ROTOR
Viscous Damping
Reference Axis
H = Angular Displacement Needed to Develop Spring Torque
Spring Restraint
V = Angular Velocity of Case About the Input Axis

The Rate Gyroscope (contd.)

Another type of rate gyro is the *floated integrating* type. It is a single-degree-of-freedom unit, in which there is no intentional restraint except viscous friction from a fluid in which the gimbal is immersed. It is also referred to as a torque-summing computer which converts input turning rates into torques that are time-integrated into gimbal displacements through a viscous fluid. Information proportional to angular displacement of the float relative to the case is obtained from a pickoff on the precession axis. The pickoff signal is generated in stator windings inside of a movable armature attached at one end of the gimbal. In some designs, the armature may rotate inside the stator.



Rate measuring gyros are widely used to provide voltage outputs proportional to the rate of turn in the following applications: airborne autopilots, fire control systems, oscillation dampers, missile stabilization and telemetering systems. Gyro rate switches are used: (a) to cut out erection in vertical gyros and stable platforms during turns, or (b) to cut out slaving voltages in directional gyros during turns.

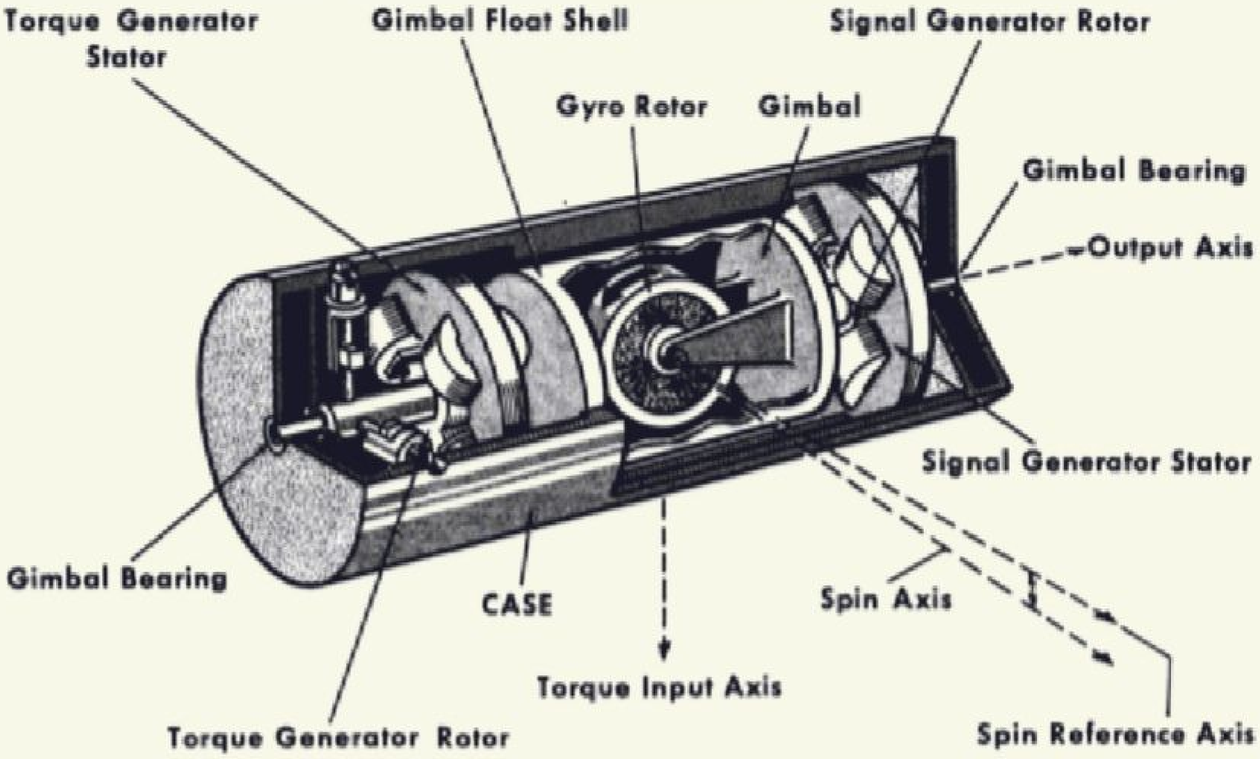

PICKOFF STATOR
PICKOFF ROTOR
DAMPING FLUID
HERMETICALLY SEALED GIMBAL
GYRO WHEEL
LIMIT STOP
BALANCING WEIGHTS
DAMPING FLUID
SEALED ACTUATING BELLOWS
ACTUATING BELLOWS
PIVOT
PICKOFF COILS
TORSION BAR
MOTOR STATOR
GYRO WHEEL BEARING (2)
MOTOR SHAFT
HOUSING
BALANCE ADJUSTING SCREWS
EXTERNAL BALANCING PORTS
JEWEL BEARING

RATE GYRO

The Floated Integrating Gyros

Floated integrating (IG) gyros are widely used as basic sensors of angular rate and angular position in a number of aircraft and missile applications — such as, in reference stabilization and navigational platforms for flight control systems, stabilization and tracking for airborne and shipborne fire control systems and rate measurement of platform deviation in missile guidance.

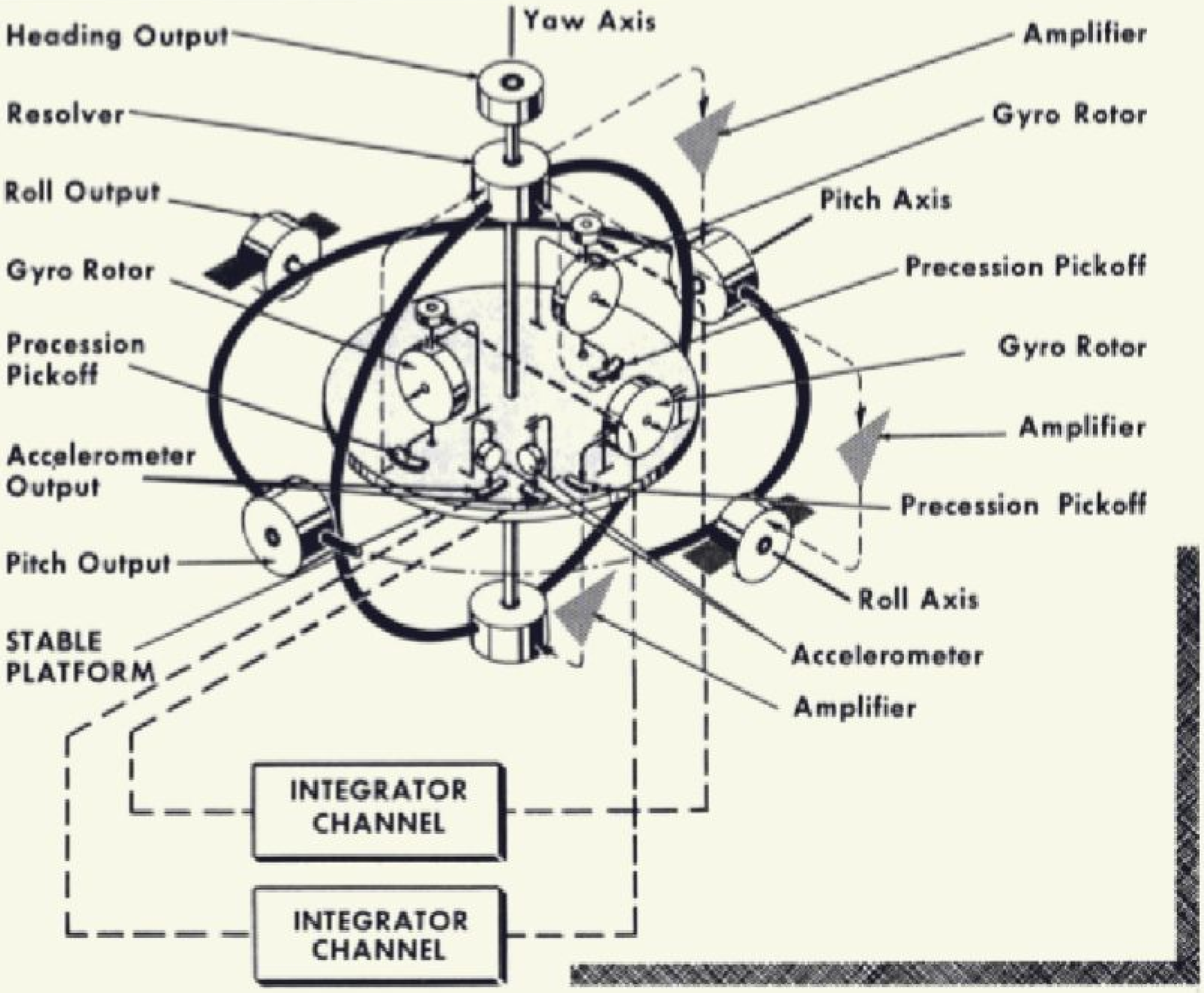
Floated, Single-Degree-of-Freedom, Integrating Gyro



A typical floated integrating (IG) gyro has its rotor in a sealed chamber filled with a gas — such as helium. The sealed chamber which really forms the single axis gimbal is mounted in a viscous fluid — such as fluorolube. The signal generator develops output voltages proportional to the precession of the gimbal, and the torque generator provides a means of inserting command signals to restore the gimbal to the proper position to balance precessional forces. In other constructions both the torque generator and signal generator are located at one end of the gimbal axis.

This type of gyro often utilizes a fluid which must be heated before it is placed in operation, due to the fact that the most suitable fluids solidify at room temperatures. Thus, a warm-up period is required before any system with which they are associated can become operational. Certain types of integrating gyros are designated (HIG) gyros for hermetically sealed integrating gyros.

Stable Platforms



THE THREE-GYRO STABLE PLATFORM

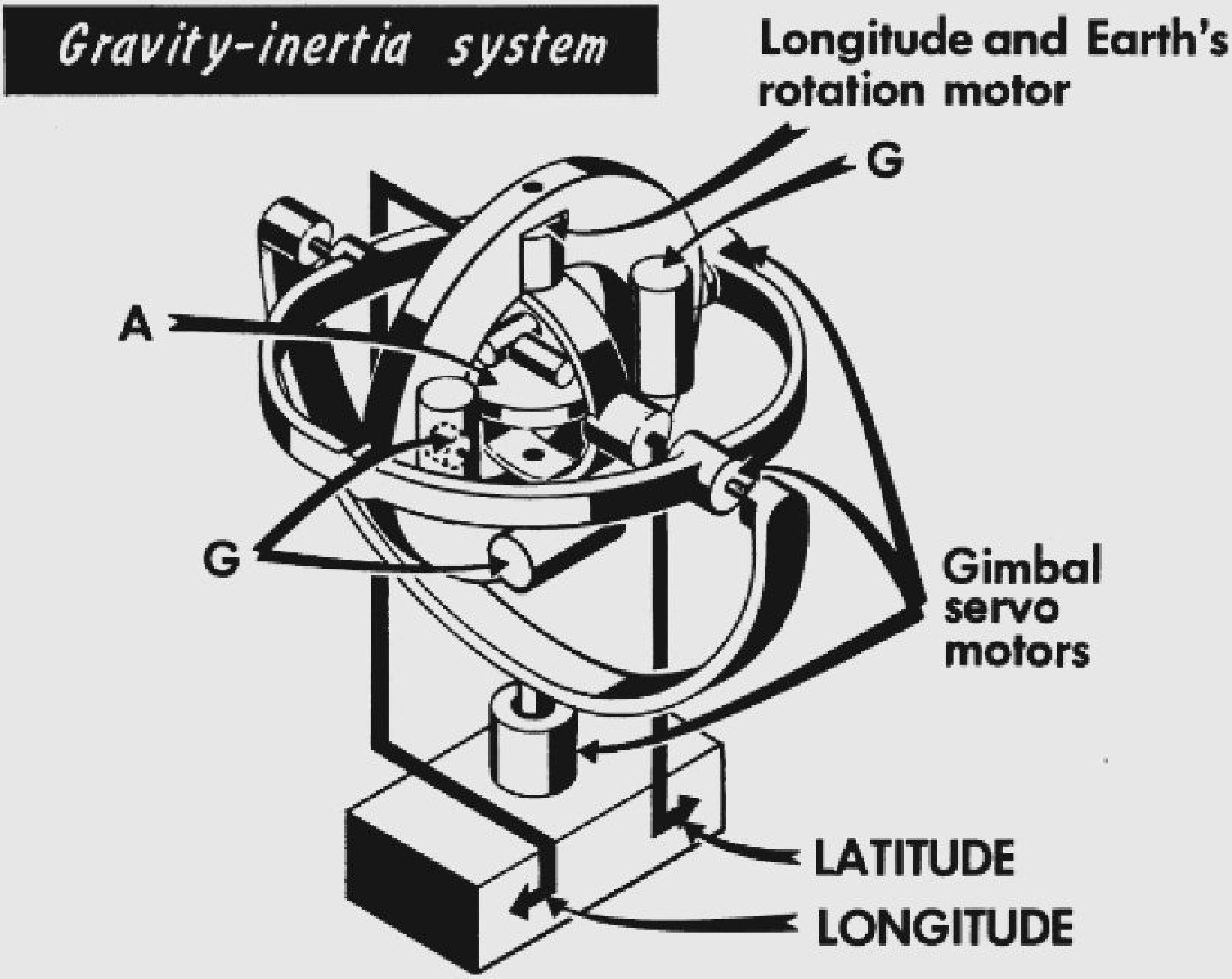
In recent years it has become more popular to utilize so-called stable platforms — consisting of either three single-degree-of-freedom gyros or a pair of two-degree-of-freedom gyros — to stabilize a system, rather than a large number of separate directional, vertical, and rate gyros to stabilize the individual units of a system. Functionally, a stable platform performs as a vertical and directional gyro combined, with a free gyro thrown in for good measure. However, it separates the gyro elements from the frame of the aircraft or missile into an integral package.

This basic design refinement improves the overall accuracy of a stable platform system to a higher degree than a system composed of a vertical and directional gyro mounted to the body of the controlled craft. The gimbaling error found in a conventional gyro is eliminated, and drift rates are lower than in conventional gyros because sensitive axis bearings are operated over only a limited range. Increased accuracy combined with the advantage of a low-volume single package make this approach a desirable one.

Stable Platforms (contd.)

The attitude information obtained from the gimbal axis transmitters can be used in several applications. Among these are autopilot reference signals, antenna stabilization, heading reference indication and verticality indication. As will be shown in following pages, the stable platform is important to inertial navigation as an accurately positioned mounting for precision-accelerometers. A three-gyro, three-gimbal platform has 360° of freedom about the roll and azimuth axes, but is limited to ±85° in pitch. By increasing the number of gimbals to four, 360° of freedom about all axes may be realized. Thus, with an additional gimbal the stable platform becomes very applicable to high performance, all attitude aircraft. However, for ballistic and cruise type missiles, three-gimbal platforms can be quite effective because they do not maneuver widely in all attitudes of flight.

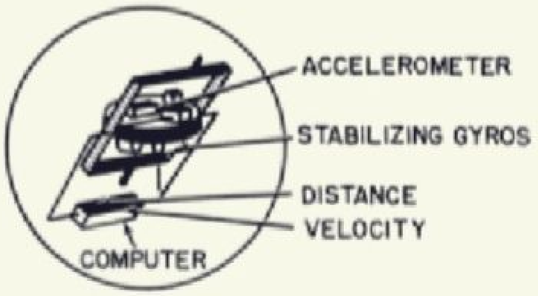
For long-range navigation along the surface of the earth, such as for ocean-going vessels, it is considered necessary to employ a five-gimbal platform, to provide for longitude and latitude corrections.


Gravity-inertia system

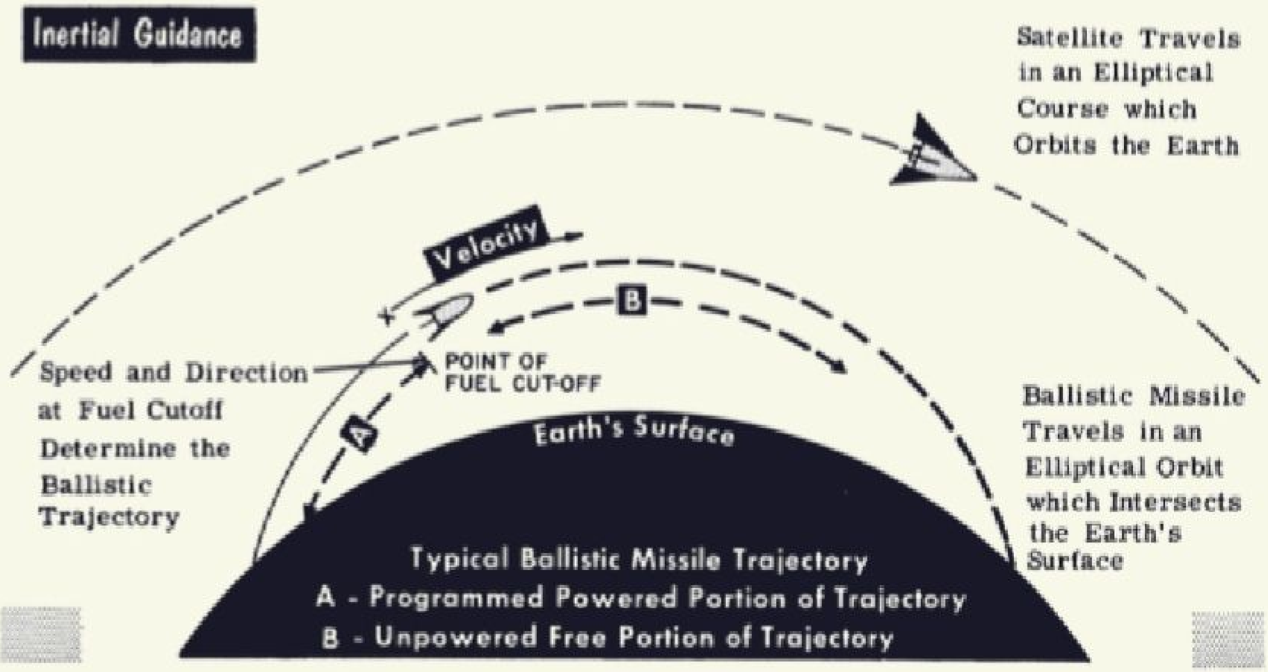
G-- Single degree of freedom gyroscope
A-- Accelerometer package

Introduction to Inertial Guidance

APPLICATIONS OF INERTIAL GUIDANCE



Inertial Guidance


Satellite Travels in an Elliptical Course which Orbits the Earth
Velocity
B
Speed and Direction at Fuel Cutoff Determine the Ballistic Trajectory
POINT OF FUEL CUT-OFF
A
Earth's Surface
Ballistic Missile Travels in an Elliptical Orbit which Intersects the Earth's Surface

Typical Ballistic Missile Trajectory
A - Programmed Powered Portion of Trajectory
B - Unpowered Free Portion of Trajectory

The range of a rocket in a typical ballistic path is to first approximation a function of its velocity (speed and direction) at the fuel cutoff or all-burnt point. Suppose we think of the ballistic trajectory as an elliptical orbit about the center of the Earth, which intersects the surface of the Earth, rather than a nonintersecting satellite orbit. Since velocity is a determining factor in the satellite orbit, it also determines the ballistic ellipse and its intersecting point with the Earth's surface.

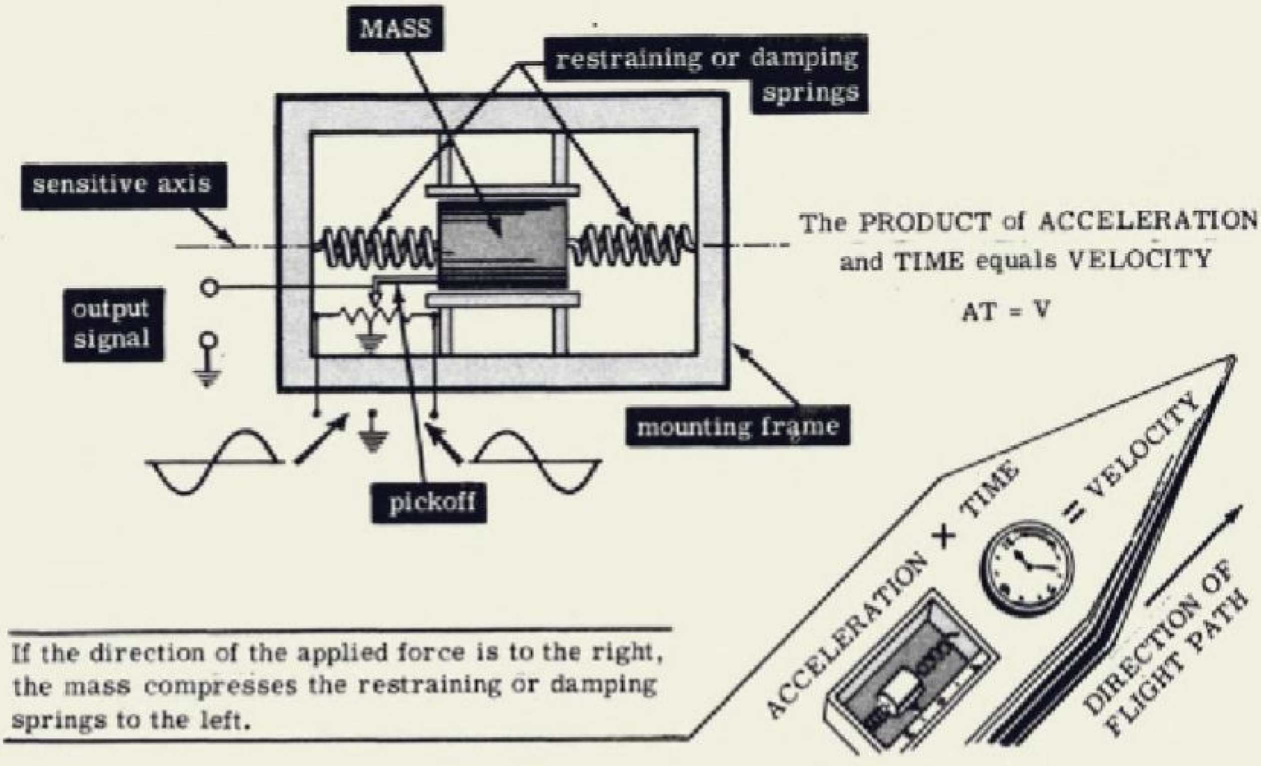
Previously we discussed how a guided missile could be brought to a point in space by a radar guide-beam technique, and how the point of fuel cutoff could be determined by measuring the velocity with a Doppler-radar system.

The initial application of another technique of a completely self-contained nature within the missile was made in one form of V-2 guidance. The missile contained a gyro stabilizer that kept it in the proper yaw and roll positions. The pitch gyro was programmed to tilt the rocket into a ballistic trajectory. To establish the proper point for fuel cutoff an accelerometer was used to determine the velocity at which this cutoff should occur.

Accelerometer Fundamentals

One of the most elementary forms of an accelerometer consists of a weight suspended between two springs. Such a simple device is never employed in a practical system. If a force is applied to move the accelerometer to the right the mass **M** will tend to remain at rest, will compress the spring portion at the left of **M**, and stretch it to the right of **M**. If a pointer is attached to **M**, it will indicate a measure of the acceleration on the scale as it moves to the left. If the applied force was in the opposite direction, the mass **M** would move in the opposite direction. Thus, the amount and direction of the acceleration can be obtained. The product of acceleration and time equals velocity. If we have a means of measuring acceleration and time, hence a means of obtaining their product by multiplication, we can obtain the velocity of a vehicle, rocket, or missile with which these measuring devices are associated.

A LINEAR ACCELEROMETER



The PRODUCT of ACCELERATION and TIME equals VELOCITY

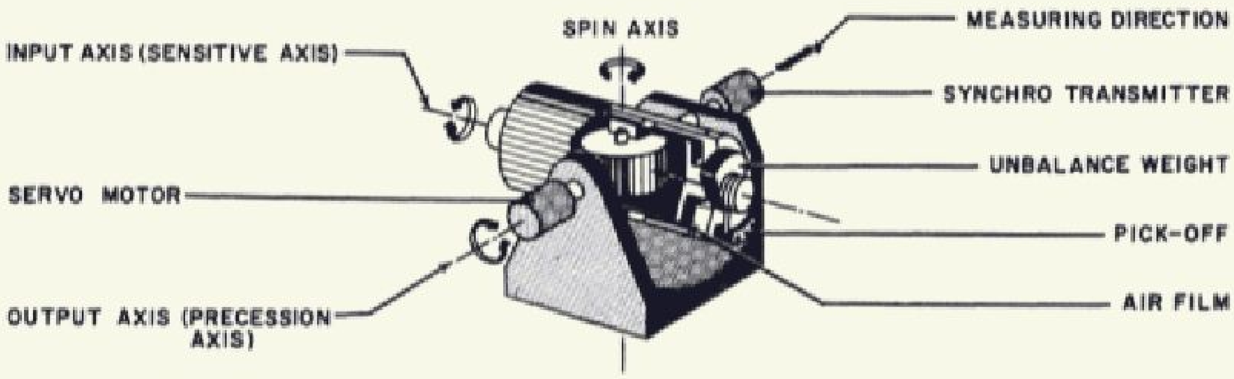
AT = V

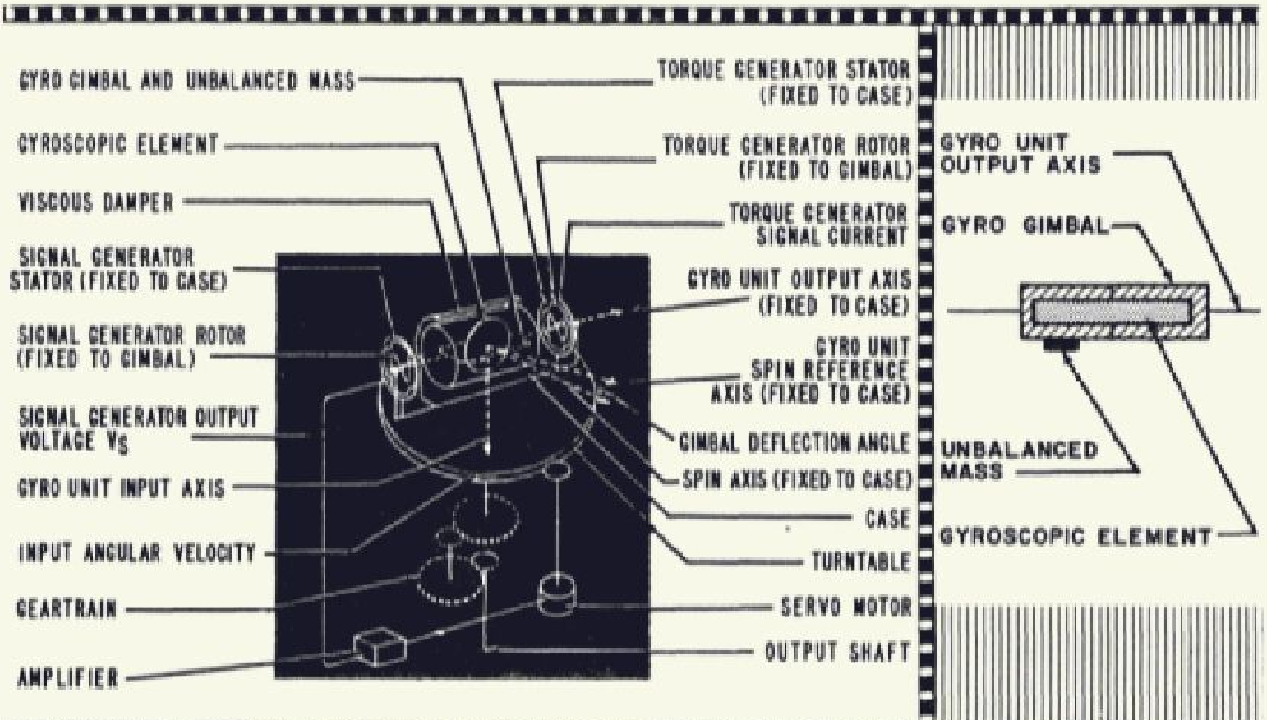
If the direction of the applied force is to the right, the mass compresses the restraining or damping springs to the left.

An accelerometer, placed along the flight axis of a missile together with a clock and computer, can measure the missile's velocity in that direction. By comparing the actual velocity to the predetermined value required to provide the desired range of flight, the fuel can be cut off at the right point. This example is one of the simplest forms of inertial guidance. It is generally employed in a somewhat more complex form, but the same fundamental principles apply. The velocity is obtained by summing or integrating the accelerations over a period of time.

The Unbalanced Gyro Accelerometer

UNBALANCED GYRO ACCELEROMETER




GYRO GIMBAL AND UNBALANCED MASS
GYROSCOPIC ELEMENT
VISCOUS DAMPER
SIGNAL GENERATOR STATOR (FIXED TO CASE)
SIGNAL GENERATOR ROTOR (FIXED TO GIMBAL)
SIGNAL GENERATOR OUTPUT VOLTAGE Vs
GYRO UNIT INPUT AXIS
INPUT ANGULAR VELOCITY
GEARTRAIN
AMPLIFIER
TORQUE GENERATOR STATOR (FIXED TO CASE)
TORQUE GENERATOR ROTOR (FIXED TO GIMBAL)
TORQUE GENERATOR SIGNAL CURRENT
GYRO UNIT OUTPUT AXIS (FIXED TO CASE)
GYRO UNIT SPIN REFERENCE AXIS (FIXED TO CASE)
GIMBAL DEFLECTION ANGLE
SPIN AXIS (FIXED TO CASE)
CASE
TURNTABLE
SERVO MOTOR
OUTPUT SHAFT
GYRO UNIT OUTPUT AXIS
GYRO GIMBAL
UNBALANCED MASS
GYROSCOPIC ELEMENT

INTEGRATING ACCELEROMETER

Before giving further consideration to accelerometer applications in inertial navigation systems, let us look at some of the forms which a guidance accelerometer may take. In some of the V-2 development work, both gyroscopes and pendulums were employed. In the gyroscopic accelerometer use was made of the fact that an unbalanced gyro, under the influence of an acceleration, precesses at a rate proportional to this acceleration. The angle of precession is proportional to the integral or summation of all accelerations over a period of time. The fuel cutoff was actuated when the gyro reached a predetermined angle of precession, and when it closed a properly adjusted contact.

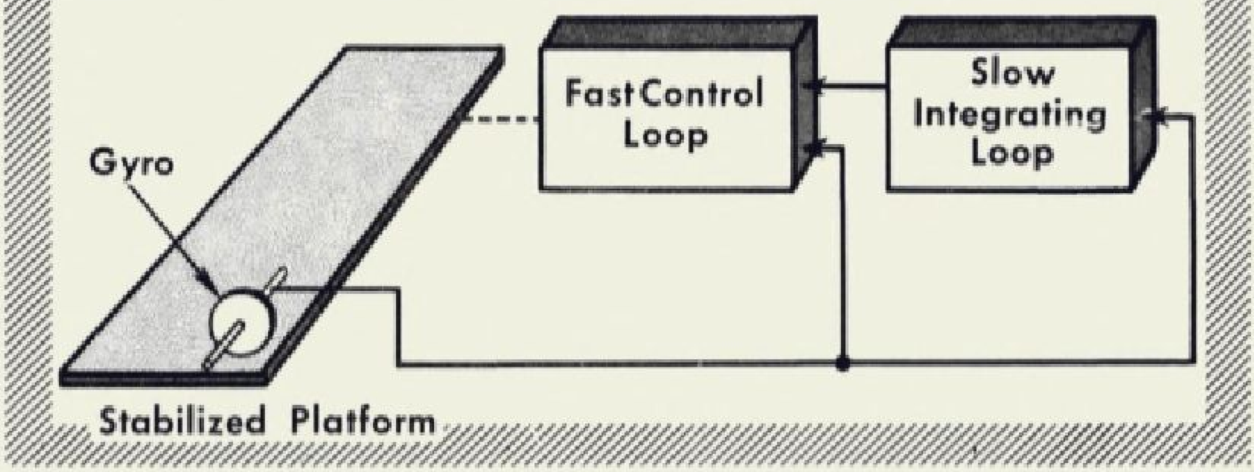
Inertial Navigation Principles (contd.)

One of the principal problems in inertial navigation is the drift of the platform-stabilizing gyroscopes from their initial setting in space. Such a drift is produced primarily by bearing friction. Naturally this is a subject of considerable study and work toward improvement in the quest for a highly accurate self-contained system of navigation. It has been shown that a .01° per hour drift rate can result in an equal navigational error in degrees per hour. Therefore, somewhat lower drift rates are sought for the platform-stabilizing gyros of cruise-type vehicles covering long ranges.

The problem is less severe for ballistic missiles where the guidance is effective for only a few minutes. The drift may be compensated to a certain extent by circuits which feed back both fast and slow deviations to the platform for stabilization. The *slow loop* does not respond to any fast deviation, but sums the error during the complete flight. The *fast loop* responds to any rapid deviations in the platform. The slow loop sums the precession required to correct for the local vertical as well as the gyro drift. This feedback minimizes the gyro-drift effect and gives an oscillatory effect comparable to the period of a Schuler pendulum (84 minutes). This effect causes the platform to oscillate slightly about its position, cancelling the gyro drift to a certain extent rather than allowing it to accumulate in one direction.

Other factors of significance in inertial systems are resolution, linearity, and scale-factor accuracy of the accelerometers. Changes in temperature, vibration, effective gravity acceleration, and the position of components are also significant. Despite these difficulties inertial navigation offers complete automaticity, invulnerability to detection and jamming, and independence from ground-based aids. However, if external references can be tolerated for realignment of the system during extended flight periods the accuracy can be greatly improved.

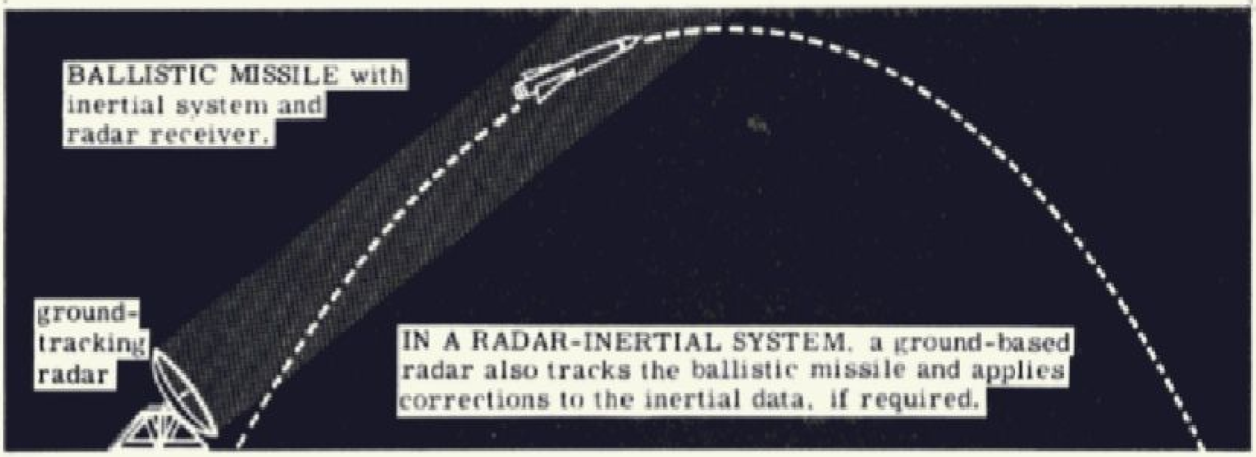
FEEDBACK FOR STABILIZATION CONTROL



External Aids to Inertial Guidance and Navigation

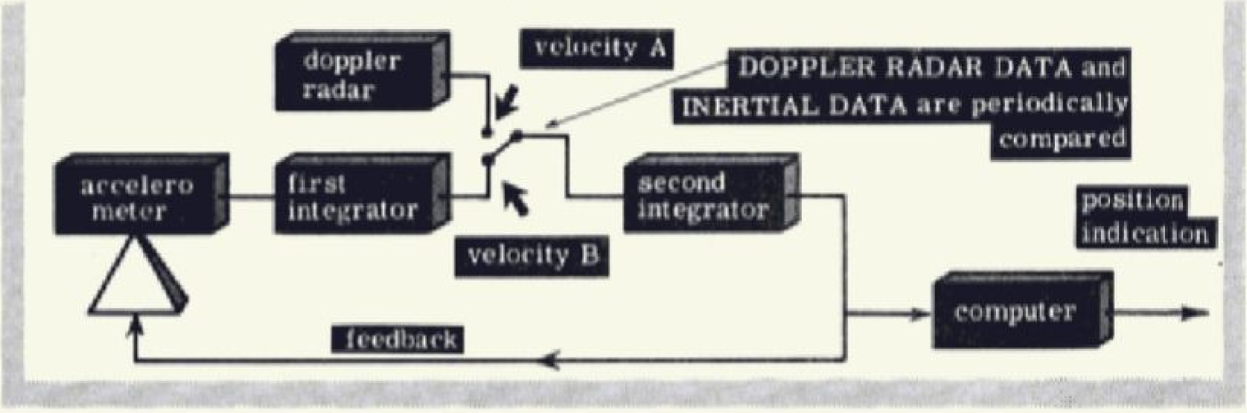
The possibility of supplementing these systems with external data offers means for correcting gyro errors. With such an arrangement the inertial system can be utilized all of the time during the guidance or navigation phase, but at periodic intervals it can be supplemented with velocity or position data from radar or celestial sources depending upon the application.

In ballistic guidance systems the radar-inertial type is of particular interest. In such a system the inertial components need not have the highest accuracy capabilities, but can be corrected by radar-tracking data.


BALLISTIC MISSILE with inertial system and radar receiver.
ground-tracking radar

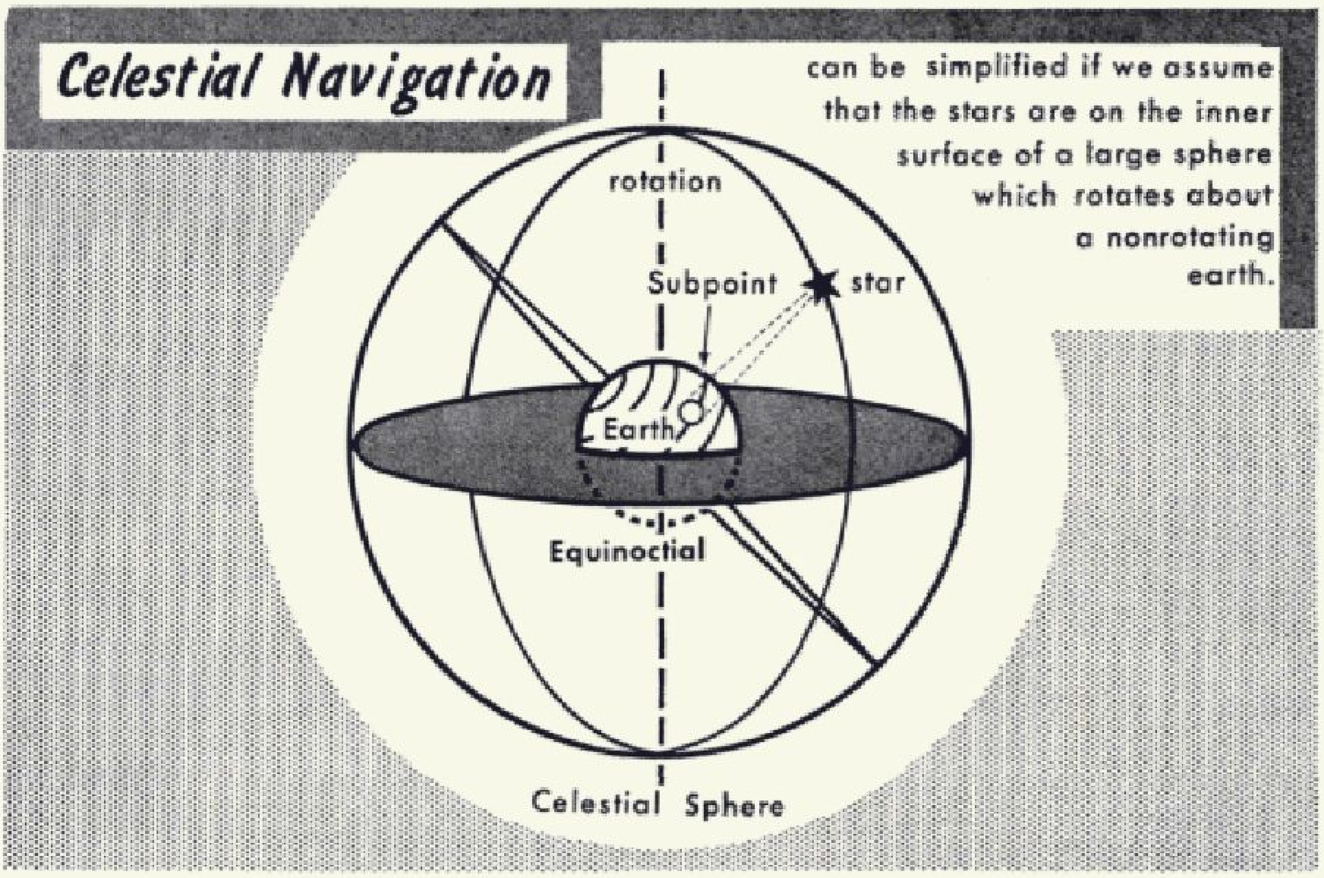
IN A RADAR-INERTIAL SYSTEM, a ground-based radar also tracks the ballistic missile and applies corrections to the inertial data, if required.

In long-range navigation applications two types of external references may be employed to assist inertial systems — namely, Doppler-radar and celestial tracking. In the Doppler-inertial system the radar equipment provides an additional source for velocity data so that comparisons can be made between the velocity measured by the pure inertial system and that obtained by the radar technique. In the celestial-inertial system the position of the vehicle is determined by an automatic star-tracker and fed in for comparison with the double integrated data of the inertial system.



DOPPLER RADAR DATA and INERTIAL DATA are periodically compared

Celestial Navigation


Celestial Navigation
can be simplified if we assume that the stars are on the inner surface of a large sphere which rotates about a nonrotating earth.
rotation
Subpoint
star
Earth
Equinoctial
Celestial Sphere

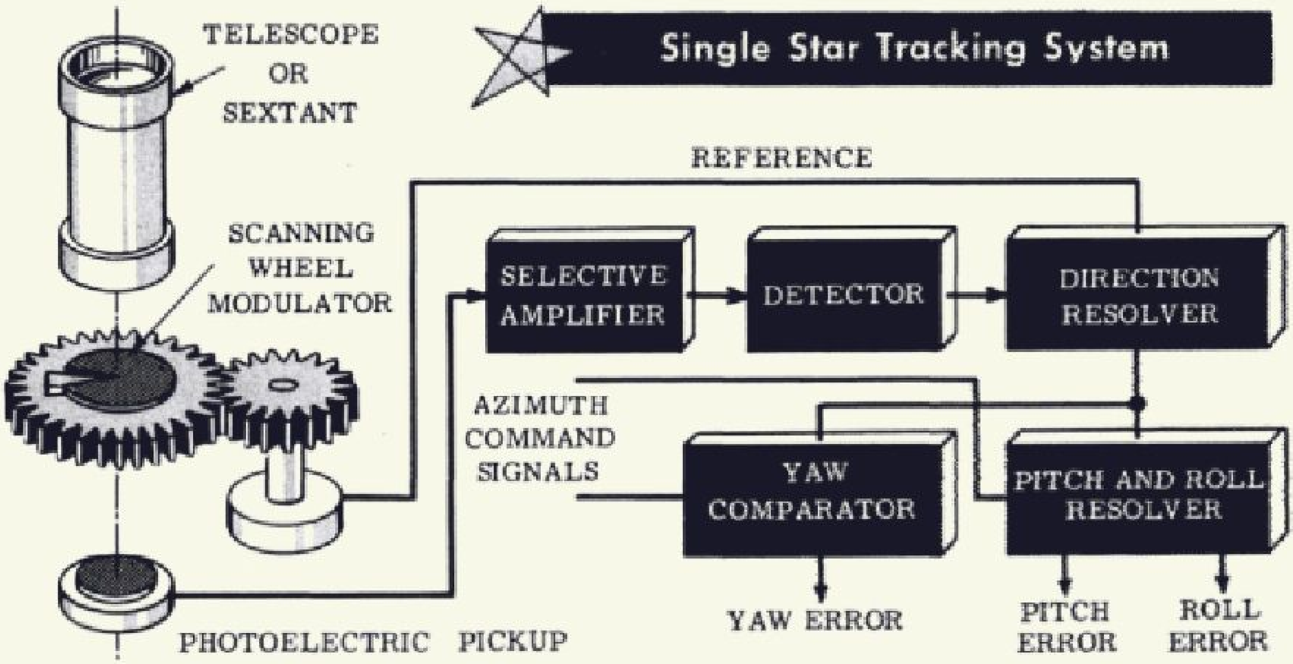
The concepts of celestial navigation can be simplified if we assume that the stars are on the inner surface of an infinitely large sphere which rotates about a nonrotating Earth. All of the stars appear to rotate westward together; however, the planets of the solar system appear to move in eccentric orbits. At any instant of time the stars on the celestial sphere appear over the Earth at corresponding subpoints. But their relative ground speeds are not the same; those nearest the Equator have the fastest apparent velocities of about 1000 mph; those in the Northern and Southern hemispheres have a slower apparent speed. In the zones of the major cities of the World, which lie between 60° North and 40° South, the minimum apparent star speed can be as low as about 500 mph. Actually it is the path traced out by any star relative to the surface of the Earth which becomes the tracking reference.

A missile or aircraft equipped with a suitable telescope and an automatic servo system to control its guiding surfaces as well as its fuel consumption could travel with a high degree of accuracy relative to such a path. However, it is not likely that a star path intersecting both the launching site and the target will be found. Therefore, rather than depending on one star path, it is better to track two stars — one whose path lies tangent to the course of the missile, the other whose path lies normal to the desired missile course. The information from the first star would be used for directional guidance and the data obtained from the second star would provide the distance reference.

The Single Star Tracking System

In a single star tracking system an optical pickup or sextant is mounted so that it can be varied in elevation and azimuth in order to follow the star path. In some arrangements a tape recorded playback or program is used to supply information for continuously aiming near the star to be tracked. The timing for this tape playback is an important function because a star is at a particular angle with respect to a certain point on the Earth only at a particular instant of time. Actually, the tape programmer brings the star tracking system within the general direction of the star, and an error-detection circuit is required to center the telescope more exactly onto the star. The outputs of this system consist of several voltages that are proportional to the missile error in pitch, roll, and yaw.

After passing through the scanner, light from the star falls on the phototube causing a voltage output proportional to the light intensity. The phototube output passes through a selective amplifier which separates the signal from the noise. The desired signal is then detected to obtain the information of the error. In the first resolver the detected signal is resolved into azimuth and elevation error signals by comparison with a reference voltage from the scanner. The direction resolver can be a bridge demodulator circuit or some type of phase detector.



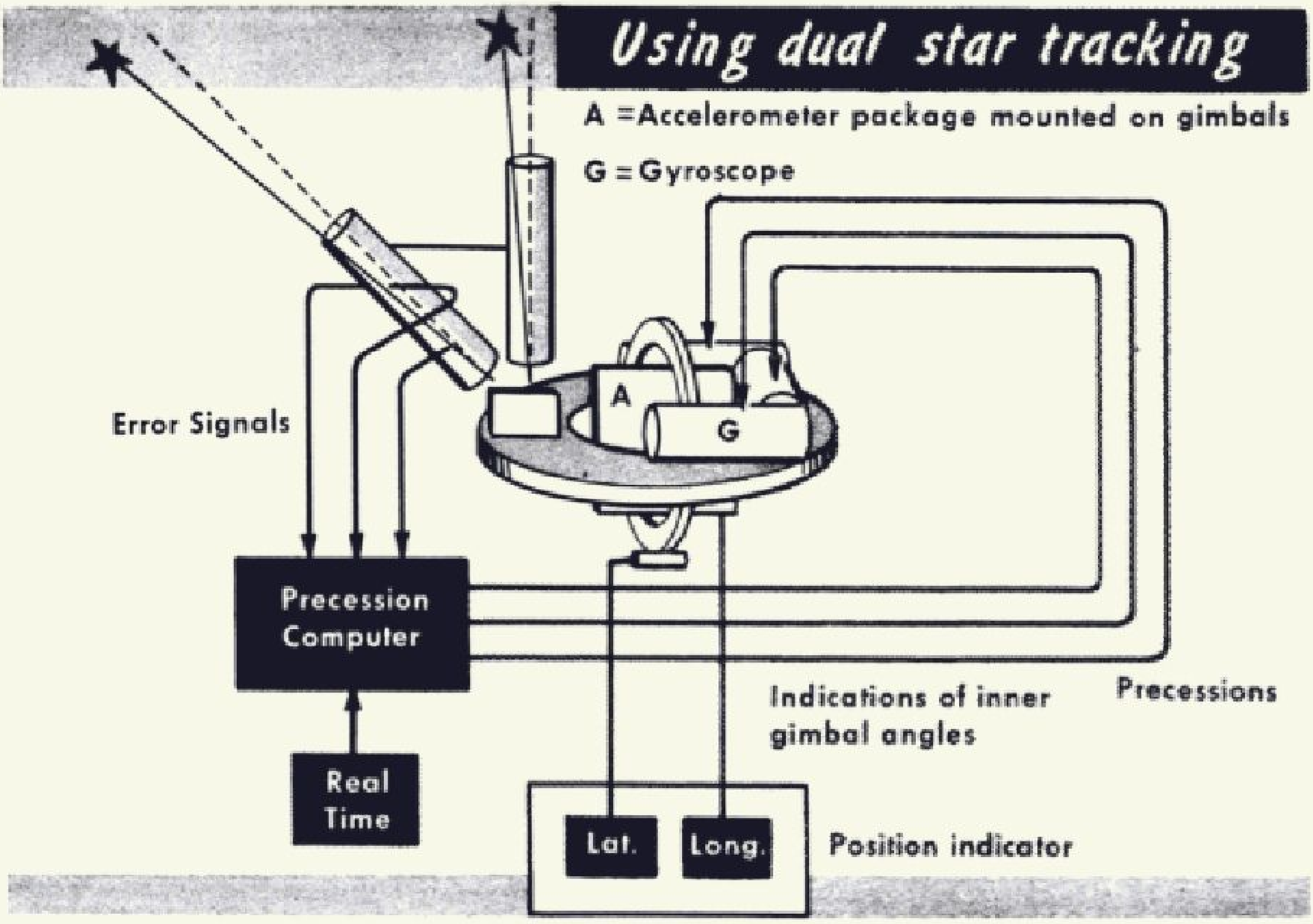
The errors are again resolved to make them usable in the missile's system of coordinates after the azimuth and elevation error in the sextant have been determined. The second resolvers are controlled from the tape reader. The same signal that sets the sextant sets a resolver for the elevation error output. If the elevation signal was not resolved in this manner, there would be no way of determining whether the error was in the pitch or the roll axis.

The Astro-Inertial System

If the telescope were elevated and pointed directly forward along the missile heading, any elevation error signal output would be attributed to error about the pitch axis. Also, if the telescope were pointed out of the side in the lateral direction, any elevation error would be only a function of roll. Therefore, the resolver is needed to determine whether the elevation error signal is due to pitch or roll, or a combination of the two.

A system better than a pure automatic celestial navigator can be realized by combining it with an inertial navigator. For instance, the inertial system can be set to provide guidance in a desired path to the target without reference to any associated information. Then, the stellar references simply aid the accelerometer and gyro combination to readjust itself for any drift or other deviations. This is certainly better than depending on finding the right star paths at the right time to give a complete guidance from those sources. Furthermore, an inertial system will operate under cloud cover or during other periods when the star references may not be available. However, in a cruise type trajectory the star information can be fed in whenever available to give data for corrections of the course which might be desirable.

An inertial system combined with a celestial tracker is known as a stellar supervised inertial autonavigator as compared with a basic continuous star tracker, which is referred to as an automatic celestial navigator.

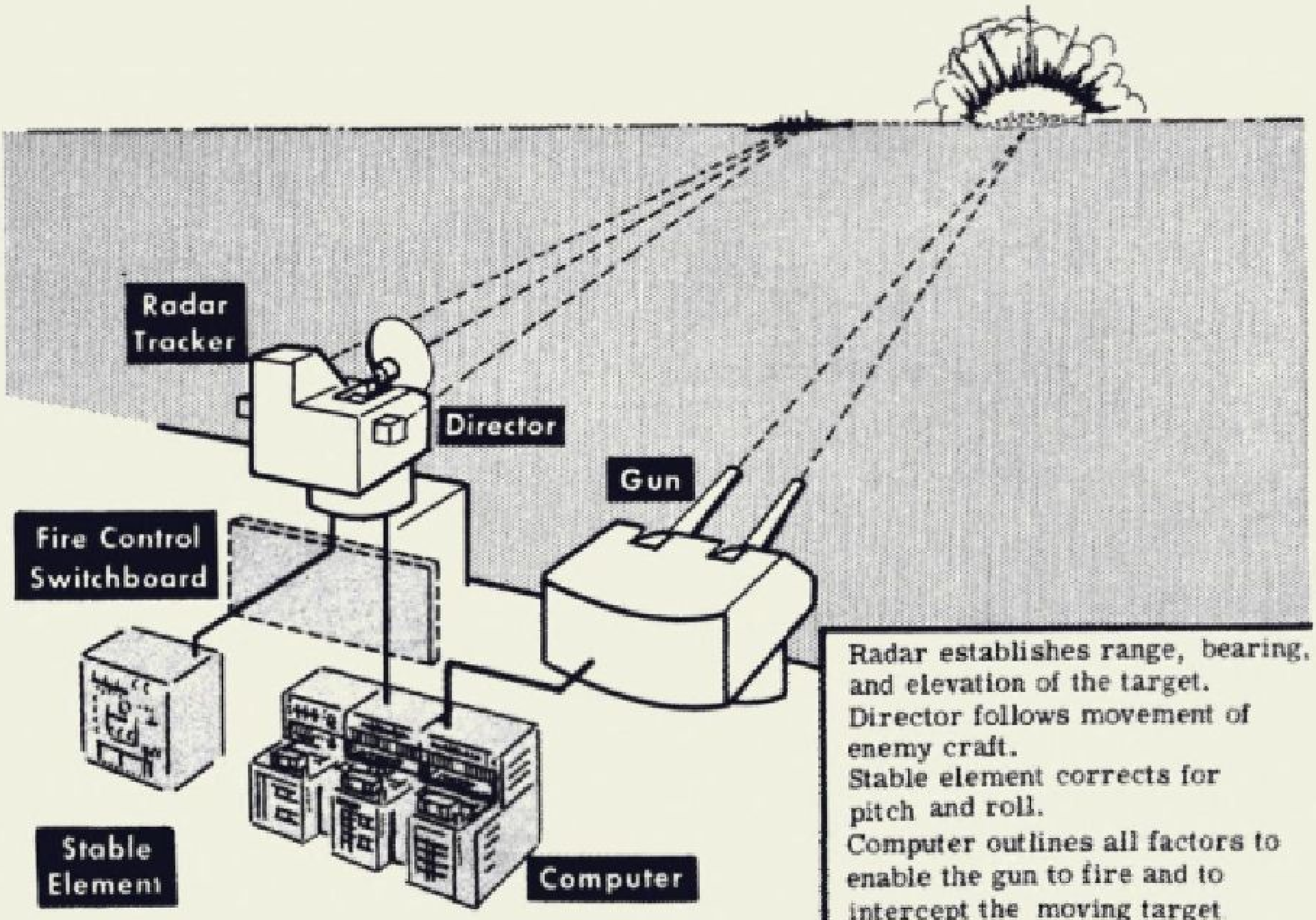


Fire-Control and Bomb-Sight Applications

One of the earliest applications of computers to a military situation was developed in gun-fire control systems. World War II saw applications of both surface and antiaircraft fire control techniques. Early in the war naval forces utilized such systems very effectively against surface vessels. Either an optical or radar tracker, mounted well above the deck, located and followed the enemy ship. It established the range, bearing, and elevation of the target, and fed this data to the computer inside the ship's plotting room. By combining these quantities the line of sight to the target was established and the director followed any movement of the enemy ship. Our ship's direction and speed also had to be fed into the computer to establish a base for computation.

A stable element corrected for the roll and pitch of the ship. Ballistic data on the shell's time of flight, trajectory corrections, and drift also were fed to the predictor, where sight-angle and sight-deflection were established. By suitably combining all of these factors with wind speed and direction, train and elevation control was made available to the guns to enable them to fire in the proper direction to intercept the moving target.

Anti-aircraft fire control followed somewhat similar steps except that the speed of the target demanded more rapid computations and gun control.



Radar establishes range, bearing, and elevation of the target.
Director follows movement of enemy craft.
Stable element corrects for pitch and roll.
Computer outlines all factors to enable the gun to fire and to intercept the moving target

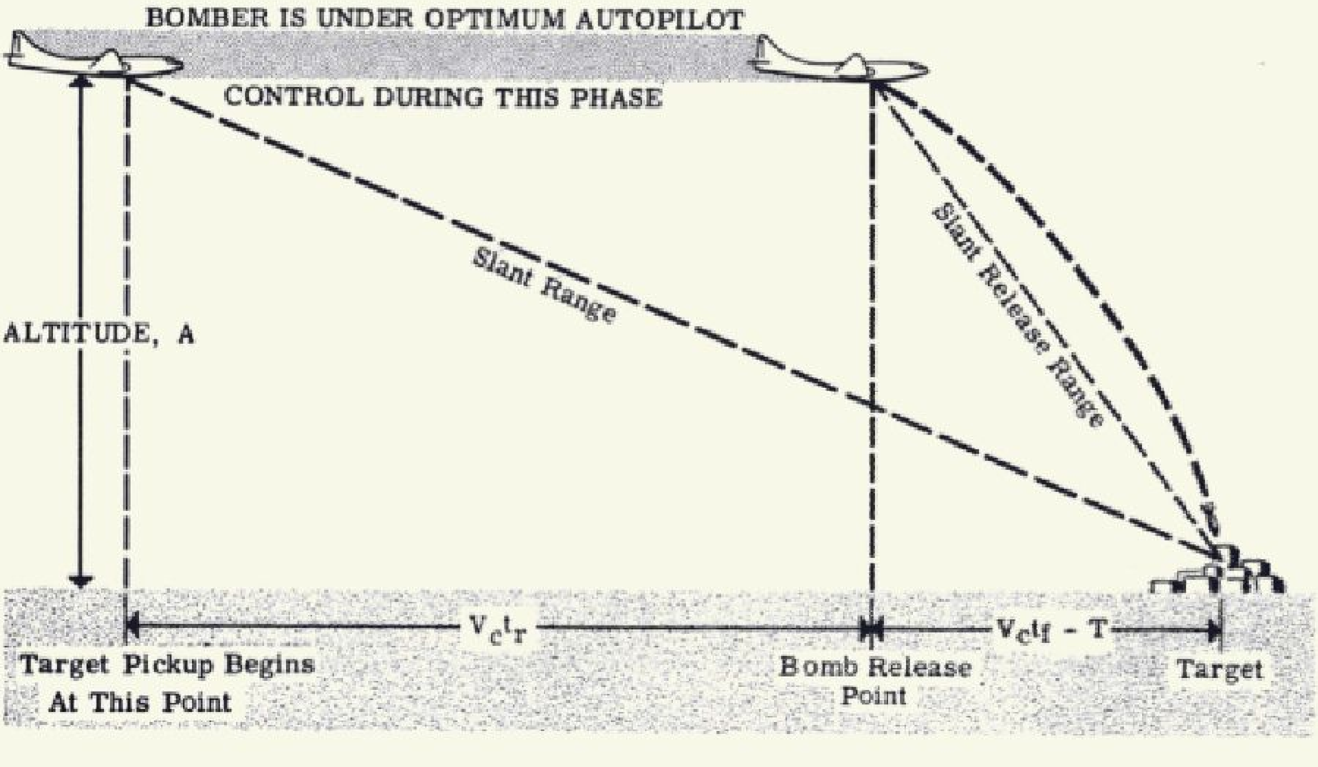
Fire-Control and Bomb-Sight Applications (contd.)

Aerial bomb-sight applications utilized the results of another early computer application — the determination of the correct range at which the bomb should be released. This distance is based on a number of factors. The time t required for the bomb to fall to the target is based on the formula, $t = \sqrt{2D/g}$, or $D = \frac{1}{2} gt^2$, where D is the distance to the target and g is the acceleration of gravity — approximately 32 ft per sec.

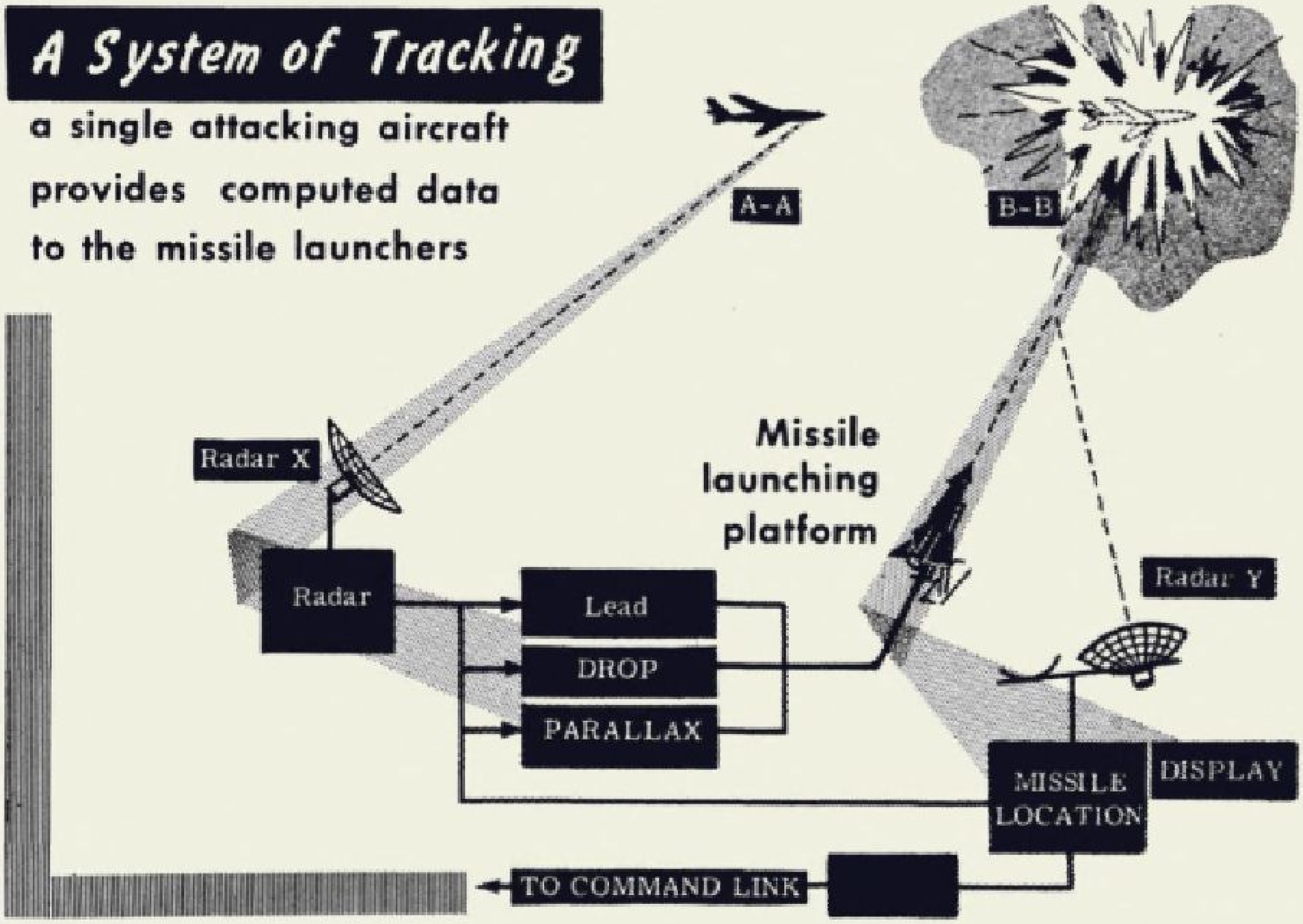
To determine the slant range at which the bomb should be released, it is necessary to calculate the vector sum of the bomber's altitude, A, and the distance between the release point and the target at ground level, R. The ground release range in a vacuum is $R = V_c t_f$, where V_c is the net closing speed of the aircraft and t_f is the time of fall of the bomb. Thus, the formula for the slant release range is $S = \sqrt{A^2 + (V_c t_f)^2}$ in a vacuum. Since the bomb will be falling through air, its range will be shortened by a distance known as the trail T, so in the air the slant release range, $S = \sqrt{A^2 + (V_c t_f - T)^2}$.

To solve the equation for slant release range the altitude, A, and the ground release range, $(V_c t_f - T)$, may be combined vectorially in a mixer-amplifier or by other means for obtaining the vector sum. If more than one bomb is to be dropped by the bomber, a factor known as *lead* is added to the ground release range. Wind velocity and direction must also be fed to the computer.

During the bomb run the operator observes the target either by an optical or radar sight and releases the bomb at the computed slant release range. During the period prior to the release the bomber is kept in stable flight by an autopilot and the sight is gyro-stabilized.


BOMBER IS UNDER OPTIMUM AUTOPILOT
CONTROL DURING THIS PHASE
Slant Range
ALTITUDE, A
Slant Release Range
$V_c t_r$
$V_c t_f$ - T
Target Pickup Begins At This Point
Bomb Release Point
Target

Command-Guidance Computers



A System of Tracking

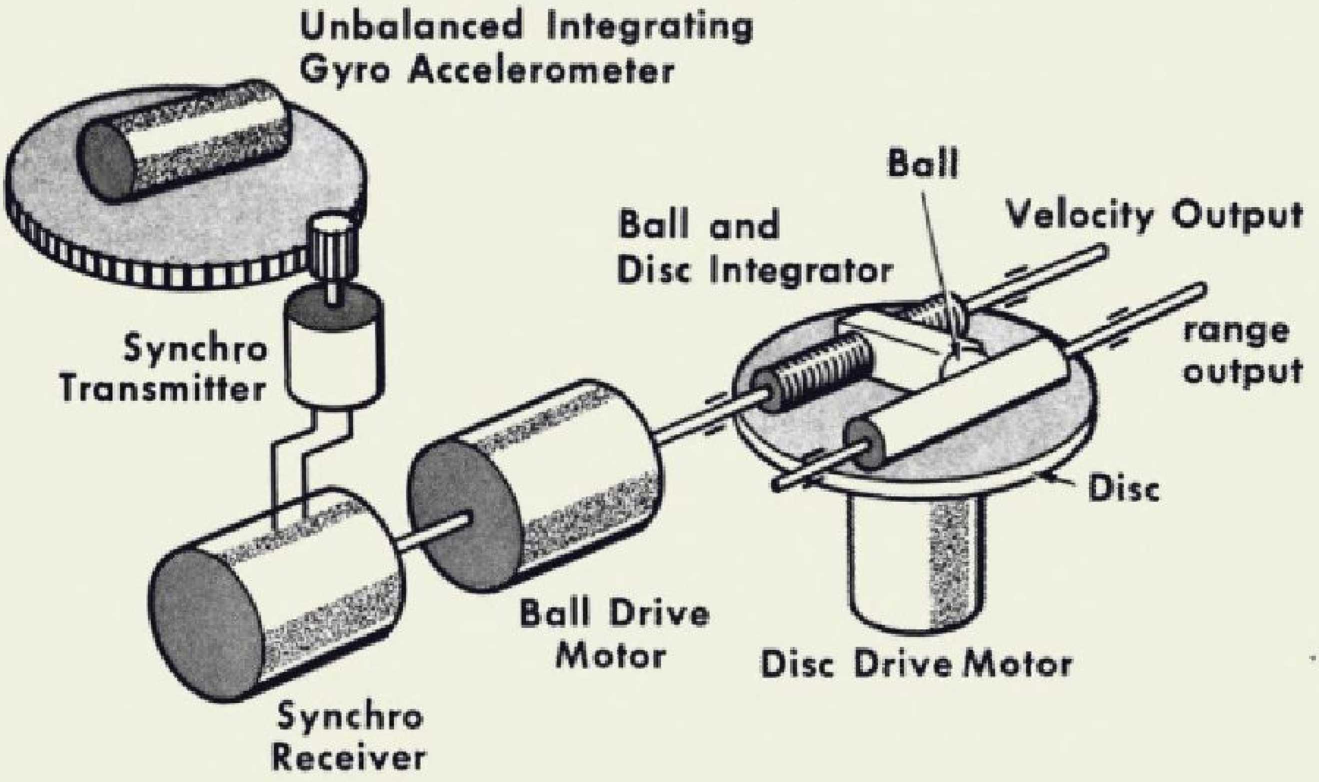
a single attacking aircraft provides computed data to the missile launchers

Surface-to-air missile guidance systems employ similar techniques to those used in antiaircraft gun-defense arrangements. In one of the first command-guidance systems for projector-launched defense missiles, a tracking radar (X) located the incoming bomber (A-A), just as in the case of the antiaircraft gun-defense technique. Another radar-signal receiving antenna (Y) tracked a beacon in the surface-to-air missile. To align the missile-launcher platform and the missile-tracking antenna properly, a computer capable of calculating the corrections necessary for lead angle, missile drop from a straight line trajectory, and parallax was employed. With this data the launching platform could be properly aimed and the operator at (Y) could follow the missile developing the proper command signals for a certain degree of accuracy. Additional computer output provided data to orient the missile-tracking antenna into the correct position relative to the roll-axis of the weapon. A missile receiver picked up the guidance commands.

The concept of tracking a single attacking aircraft and providing computed data to missile launchers is fundamental to any ground-to-air system. However, modern defense systems must embrace a much more elaborate arrangement to cope with large numbers of attacking aircraft, and provide direction to batteries of defensive weapons to be launched simultaneously against mass intrusion.

Analog Computers (contd.)

In addition to adding angles it is often necessary to integrate quantities in computers. A typical mechanical integrator is the *ball and disc* type, which has been used in bomb sights and in analog computers for missile applications. The position of the friction ball from the center of a rotating disc determines the rate at which an adjacent shaft rotates as the disc spins below the ball. The position of the ball is determined by the input applied along its rotating shaft. The number of revolutions of the shaft is a measure of the summation of the changes of the applied signals or their integral over a period of time. The output of a selsyn which is geared to the rotating shaft provides a signal for controlling the missile or for performing other functions in proportion to an integrated quantity — such as distance which equals velocity multiplied by time. Other examples of mechanical analog computers are certain types of gyroscopes that can give an integrated output if accelerations are applied to them.

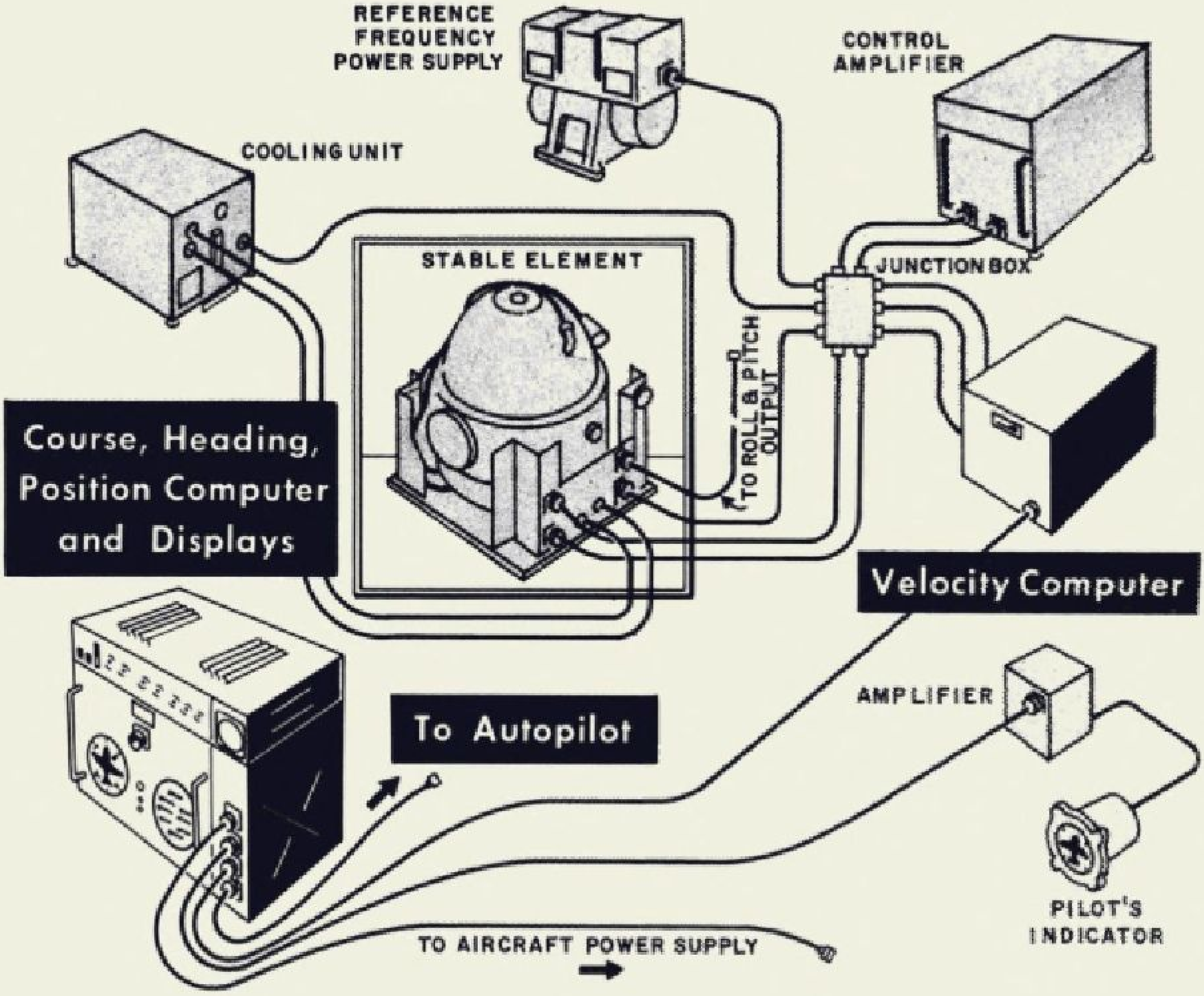


Ball and Disc Integrator provides range information from the velocity output of an integrating accelerometer

Analog Computers (contd.)

Since analog computers will perform all of the basic mathematical operations mentioned earlier in this chapter, they are employed in many missile applications. They have played a large role in the simulation of missile flight trajectories and guidance problems, permitting designers to *fly* the missile in the laboratory before it is put into expensive hardware.

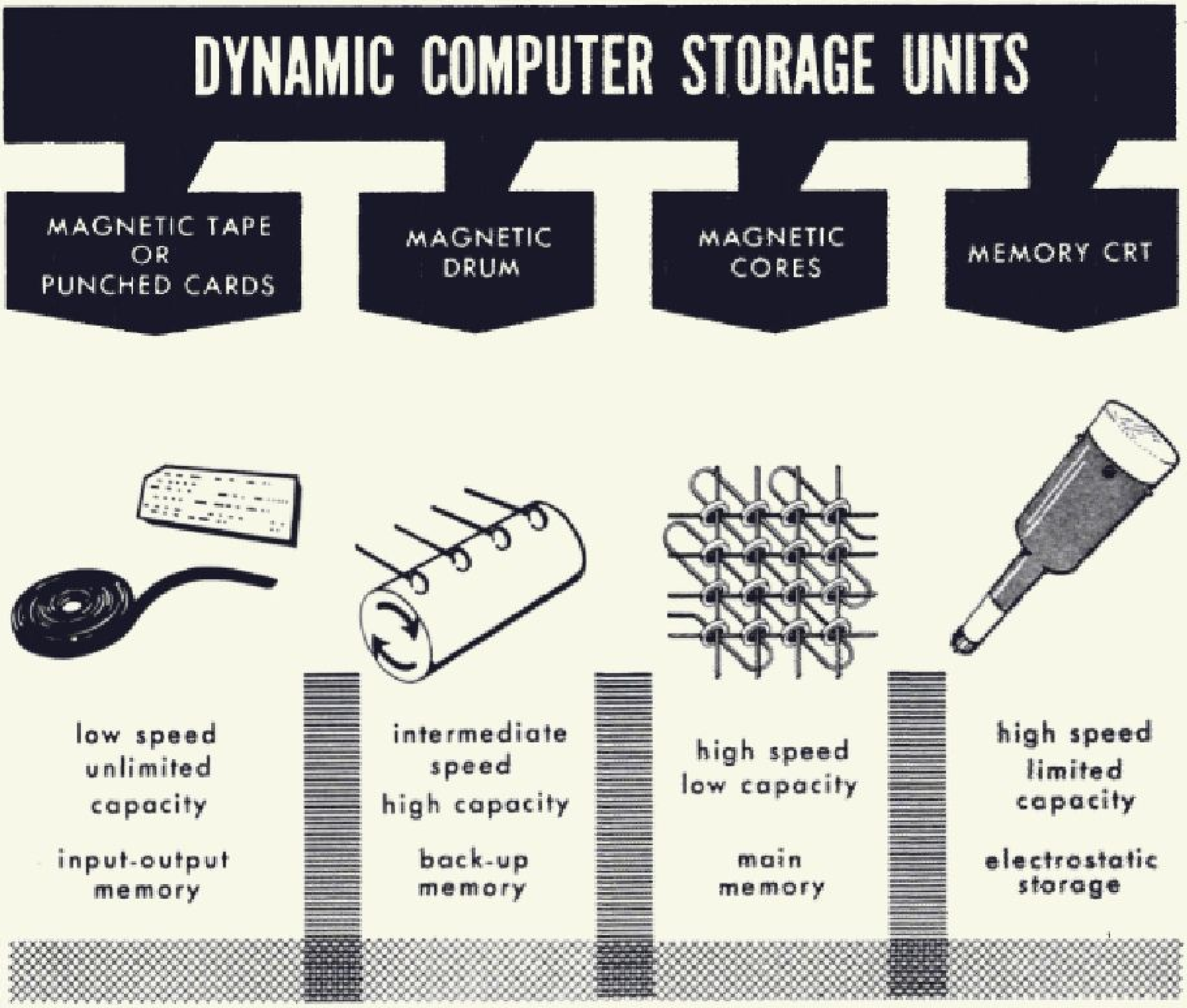
Analog computers have been widely used in high-speed aircraft to perform all of the various necessary flight and weapon-data calculations. They have also been used in many missile applications, where differentiation and integration operations are required. They have offered a weight advantage over digital computers due to some extent to the fact that much of the input data has been in analog form from the sensors, and that converters are not required. However, for many applications the trend is away from them, because they are limited in accuracies to about one-tenth that of digital computers. This situation is rather obvious when we again recognize that they do not count but simply combine analogous quantities.



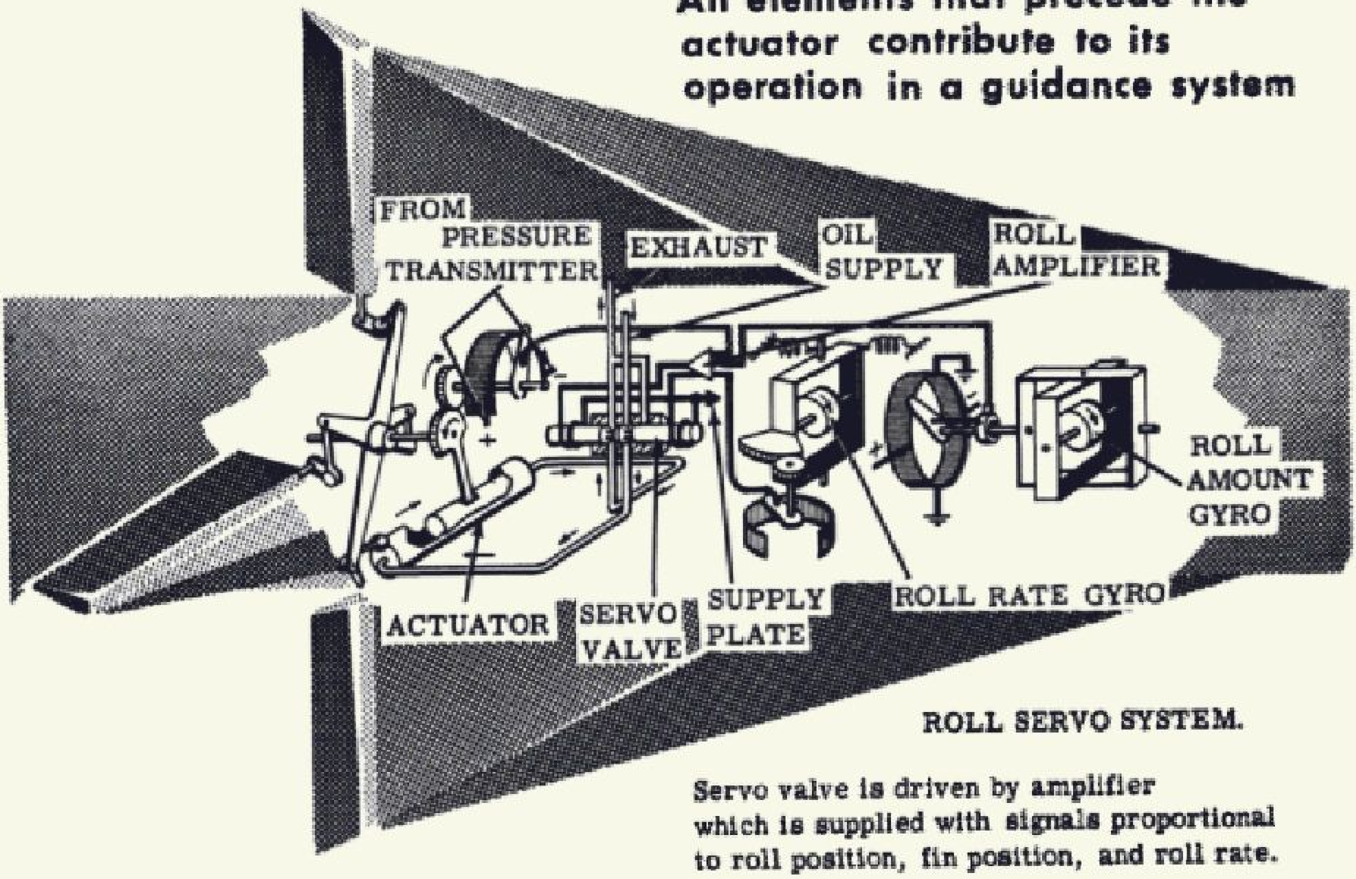
Typical Digital Computer (contd.)

Although the control and arithmetic units (sometimes, referred to as the logical section) perform the basic calculations, the memory section has been called the backbone of the system. It must store certain computations, and provide them back to the logical unit as required. Considerable research and development effort has been put forth to make it possible to tap these memory elements over and over again, if need be to accomplish the complete computations.

Undoubtedly, the human brain is one of the most remarkable storage devices. With its 10 billion nerve cells it presents a capacity considerably beyond any electronic computer storage physically possible with present-day components. Magnetic drum storage has been widely used to place as much as a million bits of information on a compact cylinder. The technique is comparable to magnetic tape recording with provision for read-out as required. A photographic method of storage, which offers a capacity of about a billion bits of information and begins to approach the human brain, has been mentioned in the literature.


DYNAMIC COMPUTER STORAGE UNITS
MAGNETIC TAPE OR PUNCHED CARDS
MAGNETIC DRUM
MAGNETIC CORES
MEMORY CRT
low speed unlimited capacity
input-output memory
intermediate speed high capacity
back-up memory
high speed low capacity
main memory
high speed limited capacity
electrostatic storage

Introduction



All elements that precede the actuator contribute to its operation in a guidance system

ROLL SERVO SYSTEM.

Servo valve is driven by amplifier which is supplied with signals proportional to roll position, fin position, and roll rate.

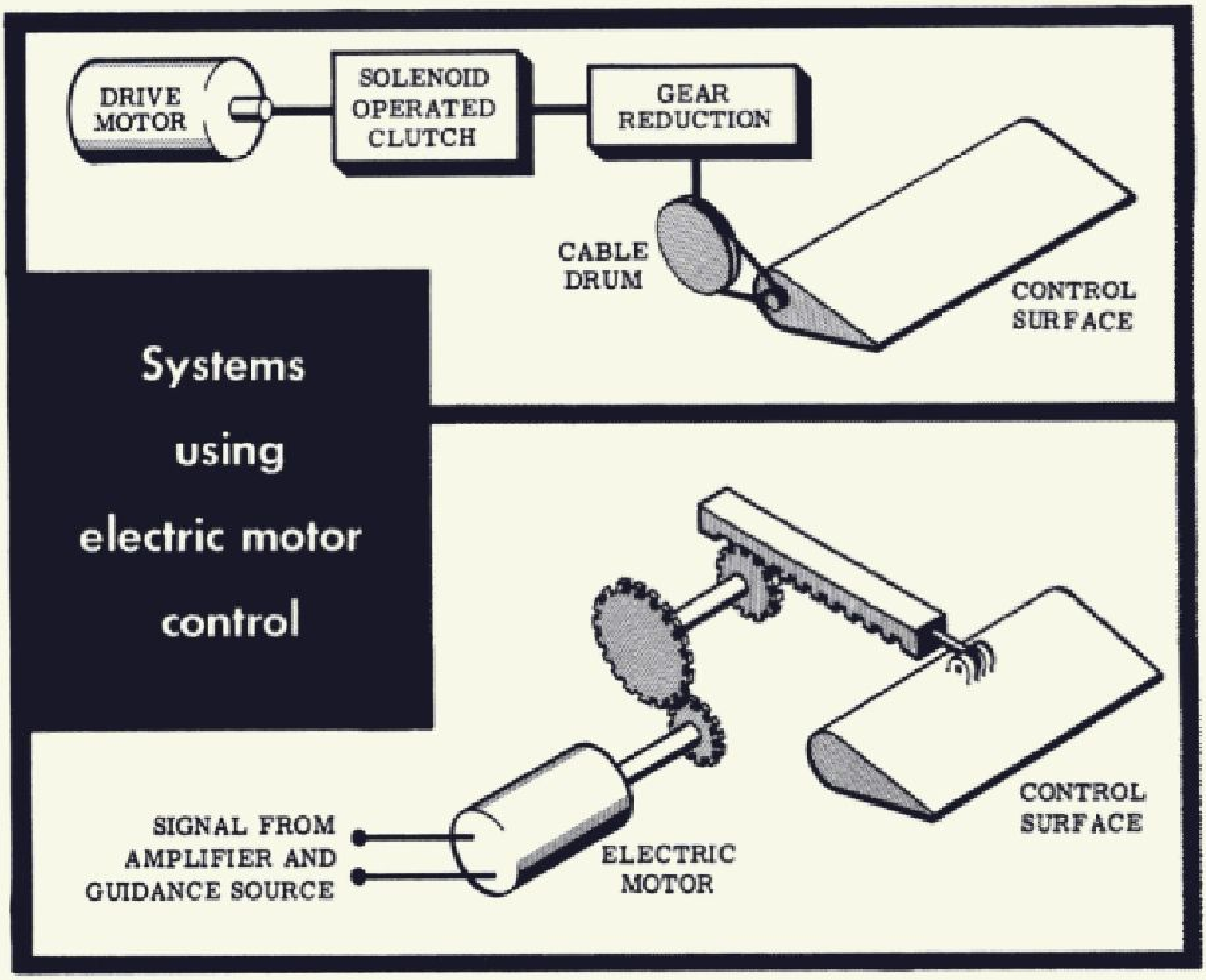
All of the guidance and control information in a missile is collected and developed for just one purpose: To supply the necessary input to the actuators of its surface- and thrust-control elements. The final objective of the control or guidance system is to move or actuate the control surfaces or thrust directors in such a way as to achieve the desired attitude or position of the craft. Thus, in a sense the actuator compares with the loudspeaker of a radio set because it is the output unit of the system. Everything that precedes it in the guidance system is manifest through it.

The escapement-controlled *rubber-band* motor-actuator of a model aircraft is a far cry from the hydraulic or pneumatic system of a guided missile. However, it demonstrates the basic principles very well, and provides enough power to control the lightweight surfaces of a very small craft. In the simple model the tension in the twisted rubber band causes the escapement arm to rotate the control rods leading to the rudder or elevator when a signal pulse is fed to the escapement coil. In the guided missile the guidance signal, whether from internal or external sensors, is fed to an amplifier which controls a valve in a hydraulic or pneumatic system. In the model craft electric motor control of the surfaces is also often employed to adjust their position. In this arrangement servomotors are caused to rotate in either direction by input from amplifiers ahead of these actuators and between them and the guidance information source.

Electric Motor Control

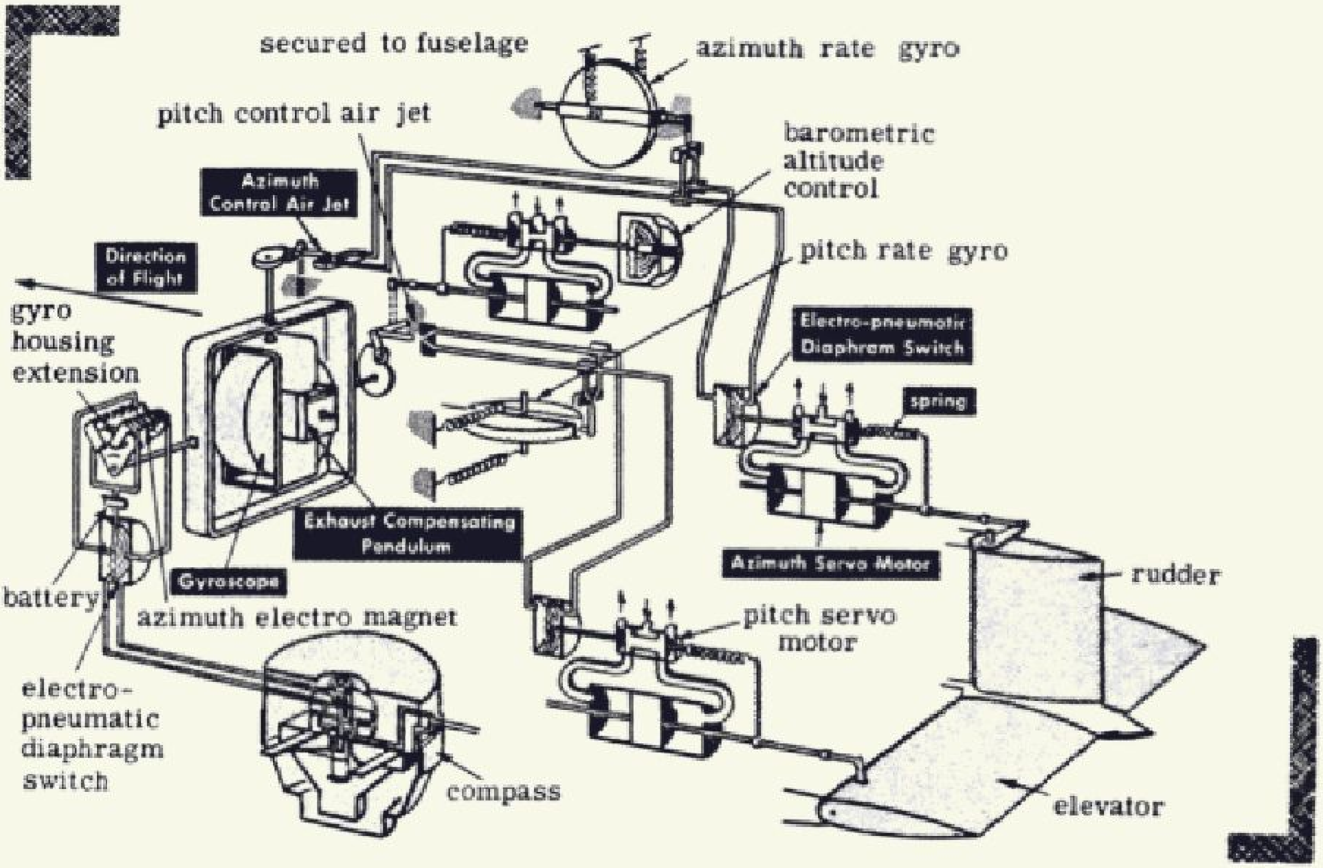
For missile guidance a most obvious approach is to utilize electric motors to drive the thrust-directors or the control-surfaces. However, a very large and powerful motor would be required to move these elements if direct drive was employed. By using a small motor, running at high speed, and geared down to the proper speed a practical arrangement can be realized. Either constant-speed motors operated through clutches or variable-speed motors are used.

Of course, there are advantages and disadvantages of electric motor-control. A major disadvantage is the fast rotation of the motor which is required to correct any sudden course deviations of the missile. It is difficult to overcome the large amount of inertia which exists in trying to suddenly reach a high-rotor and gear-train speed from a standstill. The lag introduced by this problem can easily be sufficient to make the system ineffective. Even if the weight of a large motor could be tolerated, its mass would still leave one with the inertia problem. However, two partial solutions to this problem have been realized by the development of small high-torque motors and by the use of a continuously operating motor through a clutch drive.



Systems using electric motor control

Pneumatics and Hydraulics



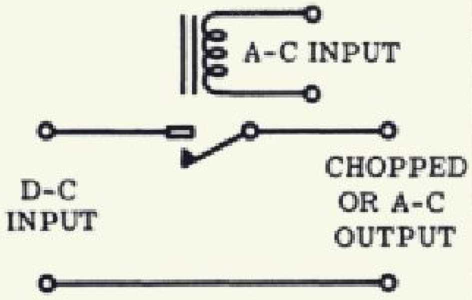
As mentioned above guided missiles require high speeds of response and large forces to move the control elements. Such requirements may be realized by either pneumatic or hydraulic systems. Although completely pneumatic systems have been employed in missiles, such as V-1 and the JB-2 pilotless aircraft, pneumatic and electrical means must be combined to be considered for modern weapons. A complete hydraulic solution is not practical in a guidance system either because it would require a hydraulic pickup from the gyroscopic and acceleration sensing-elements. Such an arrangement would exert so much force against the gyro elements that excessive errors would occur. It would also be necessary to develop a hydraulic computer. Such complete hydraulic systems appear to be practically impossible with present-day techniques and requirements. Therefore, as in the pneumatic systems a combination of electrical means and hydraulic means is essential.

Before going into detail regarding either hydraulic-electric or pneumatic-electric systems, first let us review some of the general hydraulic and pneumatic principles. Hydraulic systems are familiar to everyone in many commonplace applications, such as hydraulic brakes and transmission systems in automobiles, hydraulic lifts, and car jacks in garages. All such applications are based on Pascal's law which states that when a pressure is applied to a confined liquid, it is transmitted undiminished in all directions through the liquid; the shape of the container has no effect within reasonable limits.

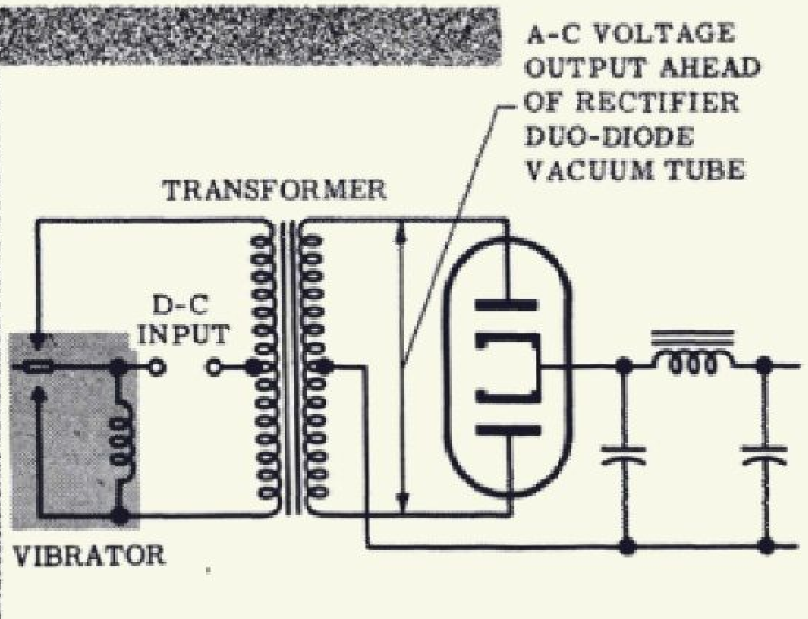
Controller Amplifiers

Between the controller and the output of a missile guidance computer we find amplifiers in practically all control and guidance systems. Since the signals may be either a-c or d-c it is necessary to have certain auxiliary devices associated with these units. For instance some system components may require d-c and some may require a-c for their operation. Thus, it is necessary to convert signals from d-c to a-c and vice versa. Typical d-c to a-c converters are mechanical choppers, vacuum tube choppers and rectifier modulators.

A mechanical chopper operates as a synchronous switch. The d-c signal is simply broken at a desired rate by contacts attached to a vibrating reed. The vibrator-type power supplies which have been so widely used in automobile radio receivers (particularly, before the advent of transistors when higher plate voltages were required for tube amplifiers) provide a good example of a full-wave chopper in which contacts are made periodically to cause current flow in two directions through split primary windings of a power transformer. In a simple version of a vacuum-tube chopper the d-c signal is applied to the control grid, and the a-c chopping signal may be applied to the screen grid so that an alternating voltage related to the d-c input appears in the plate circuit. In the case of a rectifier modulator the a-c reference voltage controls a combination of diodes in an a-c bridge circuit in such a manner that current flows intermittently first in one direction and then in the other.

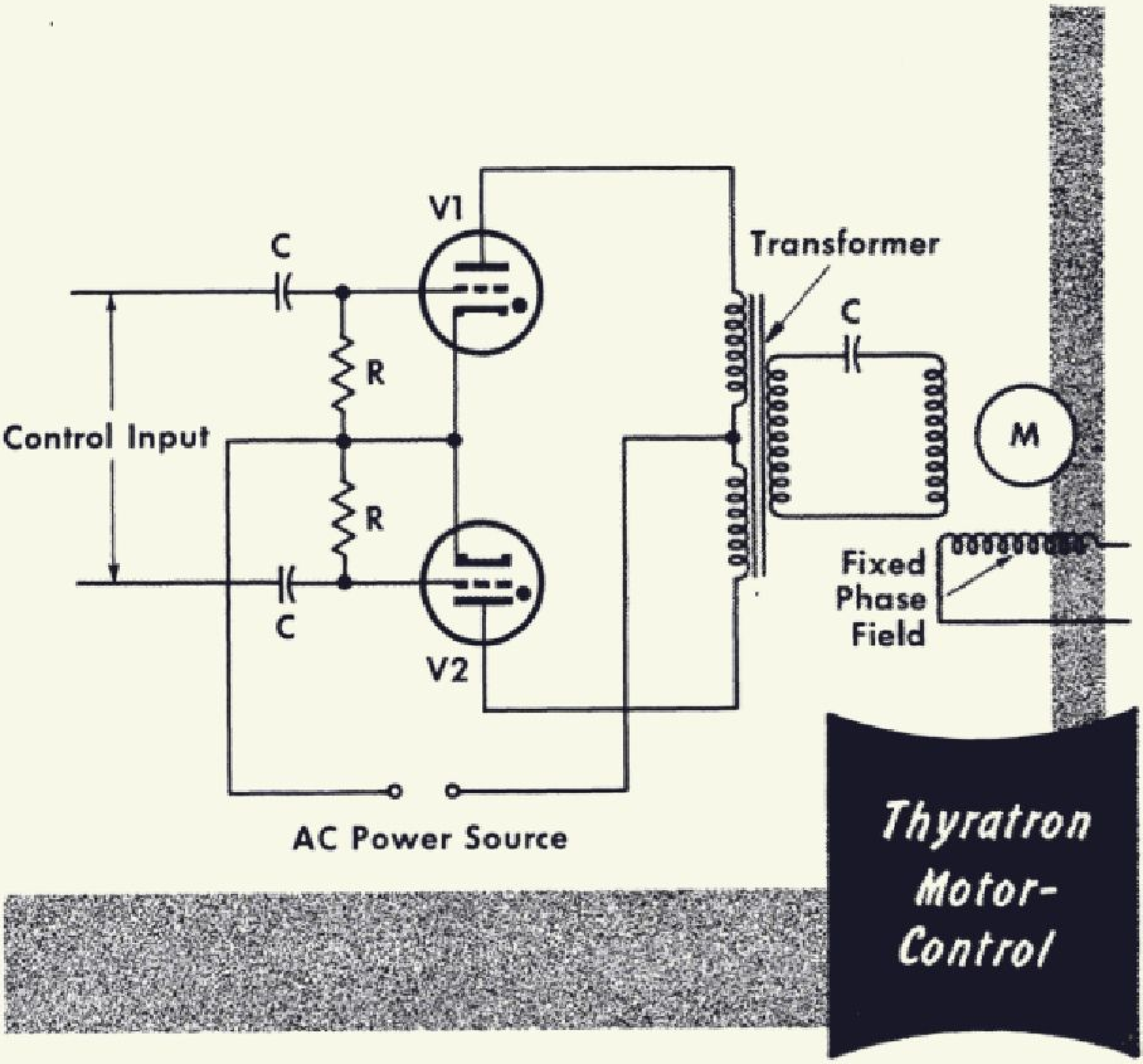


Chopper DC to AC Converter



Vibrator Power Supply

Controller Amplifiers (contd.)



Thyratron Motor-Control

Conversion from a-c to d-c is basically that of normal power-supply techniques where rectification takes place, and a d-c voltage is derived from an a-c source. Of course such an effect can also be obtained by the use of commutating rotary machinery.

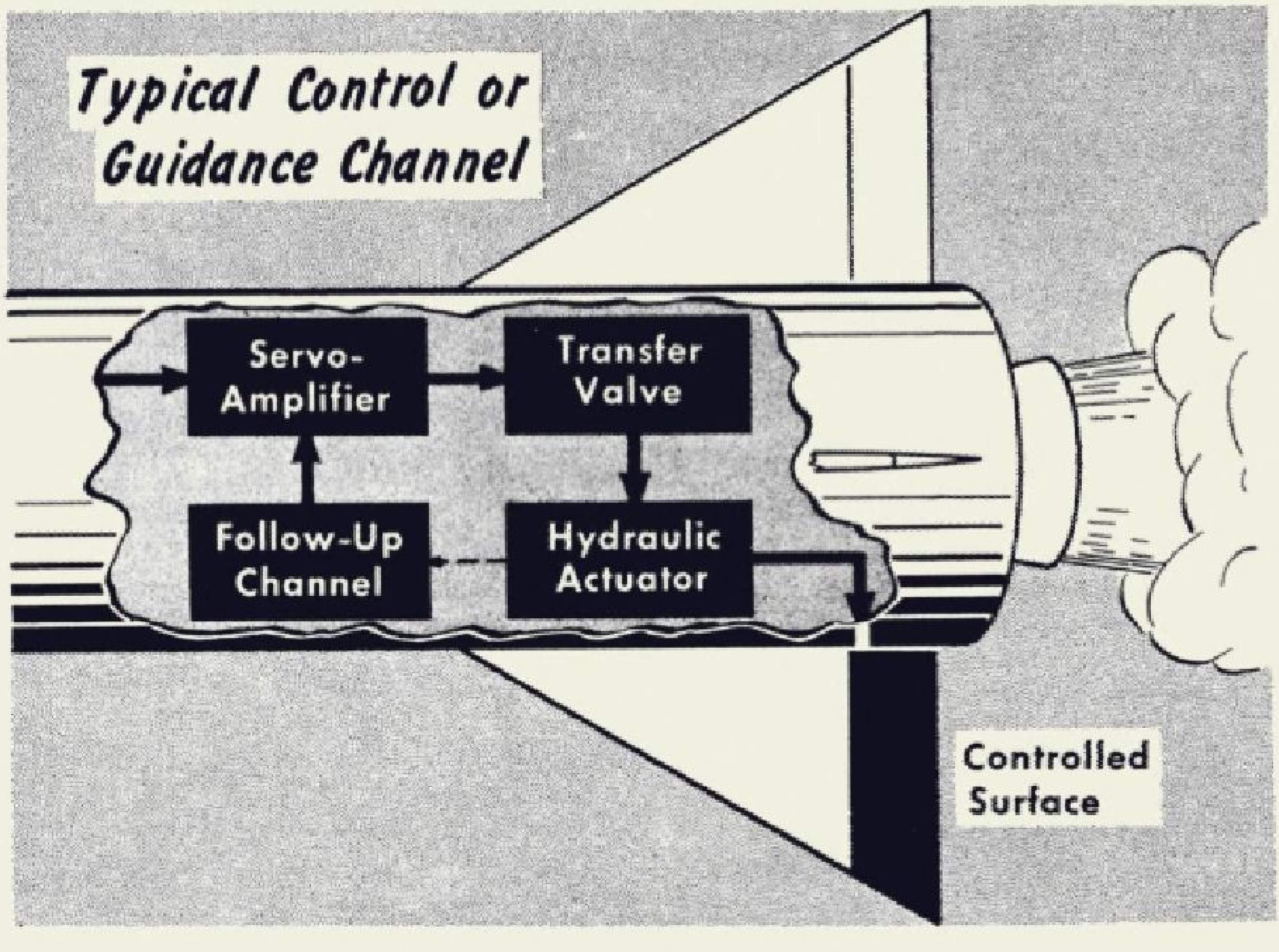
Both tube type and magnetic amplifiers are of interest in the servo-chain of missile control and guidance. Where large currents for motor control are to be handled by tube control, thyratrons can be applied. It is necessary to use gas tubes to handle the high current levels not practical for vacuum tubes.

A split-phase motor may be controlled through a thyratron circuit arrangement as shown above by supplying one field from a fixed source and the other through V1 and V2 in a push-pull arrangement. The level of the input voltage determines the amount and phase of the current which flows from the a-c source.

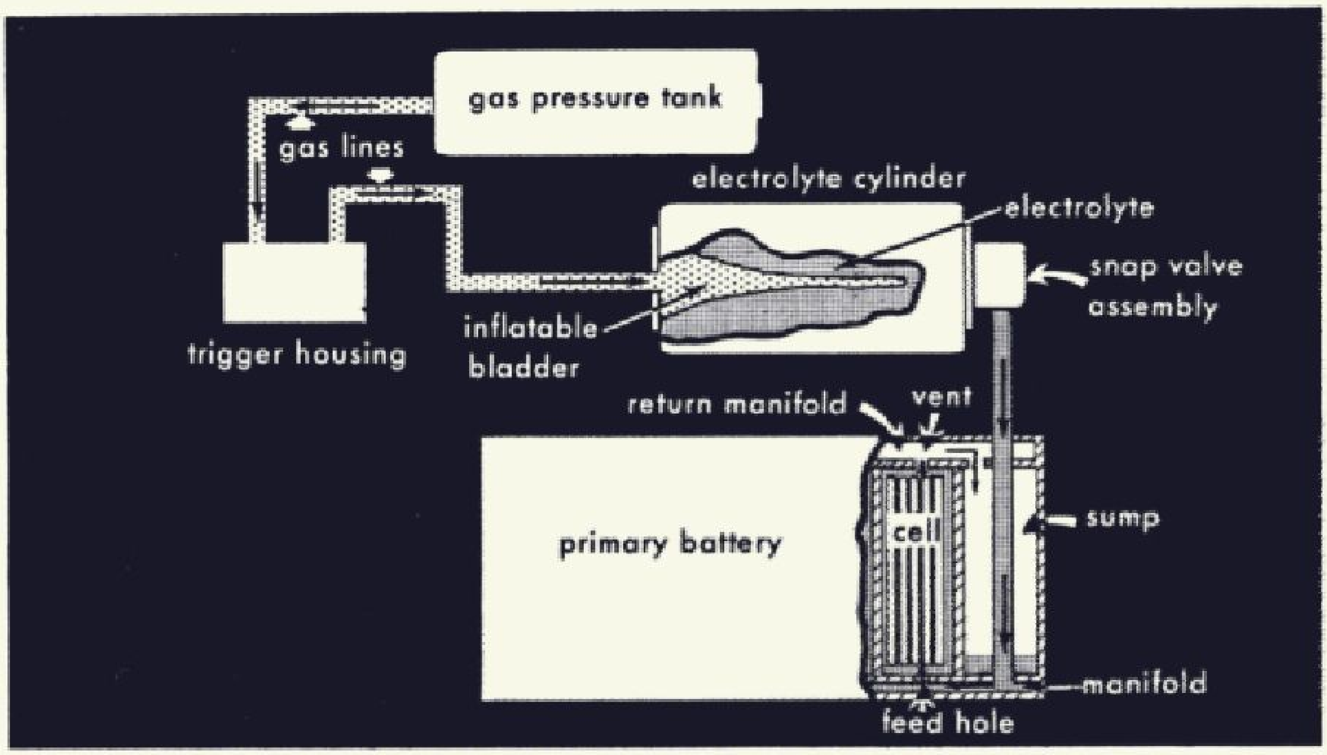
Magnetic Amplifiers (contd.)

Magnetic amplifiers suffer primarily from time-lag limitations due to inductive effects and the fact that at least one-half cycle of the a-c excitation frequency must be effective for the load current to change to a new amplitude level. Thus, if a 400 cycle a-c excitation frequency is employed, the amplifier will be able to handle frequencies only at some point below 400 cycles. For instance, it may be able to handle up to only 250 cycles. There are also considerations of waveform distortion due to nonlinear characteristics and the matter of compactness and weight. Transistors have considerable advantages in regard to weight and compactness, and are being used more widely as their power handling and temperature capabilities are improved. They may be combined with magnetic amplifiers to obtain faster response through negative inductance compensation.

Another facet of a complete control or guidance channel is the follow-up amplifier. This unit feeds back to the servo amplifier a signal proportional to the actual output at the actuator. By so doing it tends to stabilize the system, just as a negative feedback channel in an audio amplifier tends to dampen oscillation or other violent swings of motion. A loop through the servo amplifier, transfer valve or controller, the actuator and the follow-up unit completes such a picture. A typical loop with a hydraulic system is shown.



Auxiliary Power Supplies



BLOCK DIAGRAM OF AUTOMATIC ACTIVATION SYSTEM

An important aspect of any control channel as well as the entire control and guidance system is the auxiliary power supply. In the case of the hydraulic-electric and pneumatic-electric systems, power sources for pressurizing the liquid or gas must be available as well as electrical power for all of the electronic portions. Such sources are called APUs — an abbreviation for auxiliary power supplies. Three basic types have been employed in a variety of missile designs — (1) batteries, (2) cold gas, and (3) hot gas systems. Requirements vary with the type of missile from short duration one-shot applications to longer duration higher level demands.

For smaller missiles in particular and some larger missiles, batteries have often been employed as the *APU*. They supply low voltage electrical power directly and can drive alternators and the hydraulic pump through a motor. Primary batteries, such as the silver-zinc type, are usually employed. Battery APUs generally have a long storage life because they are kept in an inert condition until missile launching time. Then the electrolyte is forced into the cells to activate them by discharging a carbon-dioxide or hot gas squib associated with it.

Although battery systems have been able to realize competitive power per pound and unit volume through design advances, much of these gains are lost due to the necessity of operating an electric motor for the hydraulic pump. Due to the weight of the motor it is not likely even with higher voltages that the battery APU will be able to compete with the hot gas APU and its lighter turbine.

Auxiliary Power Supplies (contd.)

Cold gas APUs are usually employed for short-time applications to power only the hydraulic system. The prime power is supplied from a high pressure gas source. As the missile is launched, the power source is activated by an arming mechanism which punctures the sealed gas. In some of these systems the sealed-gas pressure is too high to use directly so it is followed by a regulator to reduce the pressure to a somewhat lower level. In its operation gas flows at the proper pressure to an accumulator-reservoir unit, where it powers the hydraulic fluid to the valves and actuators.

In hot gas APUs either monopropellant or bipropellant fuels are converted into high pressure gas in a combustion chamber. The gas is directed in a jet to a turbine wheel which drives both the hydraulic pressure pump and the alternator to supply electrical power to the electronic portion of the missile system. The system may be regulated by a hydraulic pressure feedback which acts to control the opening of the turbine nozzle. Electrical feedback may also be applied from the alternator through a magnetic amplifier to control the flow of fuel to the combustion chamber. Hot gas APUs offer the advantage of high energy per pound of fuel.

ACCESSORY POWER SYSTEM